Carbon Footprint Estimation of Municipal Water Cycle

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at George Mason University

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ABSTRACT

CARBON FOOTPRINT ESTIMATION OF MUNICIPAL WATER CYCLE

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This research investigates the embodied energy associated with water use. A geographic information system (GIS) was tested using data from Loudoun County, Virginia. The objective of this study is to estimate the embodied energy and carbon emission levels associated with water service at a geographical location and to improve for sustainability planning. Factors that affect the carbon footprint were investigated and the use of a GIS based model as a sustainability planning framework was evaluated.

The carbon footprint metric is a useful tool for prediction and measurement of a system's sustainable performance over its expected life cycle. Two metrics were calculated: tons of carbon dioxide per year to represent the contribution to global warming and watt-hrs per gallon to show the embodied energy associated with water consumption. The water delivery to the building, removal of wastewater from the building and associated treatment of water and wastewater create a sizable carbon footprint; often the energy attributed to this water service is the greatest end use of electrical energy. The embodied

energy in water depends on topographical characteristics of the area's local water supply, the efficiency of the treatment systems, and the efficiency of the pumping stations. The questions answered by this research are: What is the impact of demand side sustainable water practices on the embodied energy as represented by a comprehensive carbon footprint? What are the major energy consuming elements attributed to the system? What is a viable and visually identifiable tool to estimate the carbon footprint attributed to those Greenhouse Gas (GHG) producing elements? What is the embodied energy and emission associated with water use delivered to a building?

Benefits to be derived from a standardized GIS applied carbon footprint estimation approach include:

- Improved environmental and economic information for the developers, water and wastewater processing and municipal planners
- Improved energy use reporting and conservation planning
- Establishment of a benchmark for GHG emissions attributed to the water and wastewater industry
- Ability to quantify relative impacts of building design options using carbon emission equivalents

The GIS based model was applied to the Dulles South and Brambelton regions in Loudoun County, Virginia. The GIS revealed the customer's embodied energy to be in

the range of 4.41MWh/Mgal to 8.0 MWh/Mgal. The customer's carbon footprint is between 0.008 and18.0 Tons of CO_2 for year 2008.

The results of this study contributed to development of a standardized approach to estimate the GHG impact of a total water cycle, and provided a viable GIS tool resulting in visual maps as a decision support. It also showed the use of derived empirical formulas in predication of GHG impact for end users in a specific geographical area. The embodied energy in delivered water can be estimated using the devised model and be considered by the building sustainability ranking programs such as the USGBC LEED rating system.

KEYWORDS

Water Life Cycle, Embodied Energy, Global Warming Potential, Energy Intensity, Energy Intensity Matrix, Emission Intensity, Emission Coefficient, Carbon Dioxide Emission, Water and Wastewater, Collection, Treatment and Distribution, Carbon Footprint, Topography, Municipality, Environmental Indicator, ArcGIS, LEED, GHG, ESI, LCA, LCEA, LCI, Sustainability, End Use, Potable Water

CHAPTER 1 – INTRODUCTION AND OVERVIEW

There is a connection between energy consumption and water use. Energy is required to produce water for consumptive uses. This has led researchers to explore the total environmental impact of the water sector as it relates to energy use and greenhouse gas emissions. This research investigates a methodology for determination of greenhouse gas impact resulting from water consumption by end users located in a geographical region. There are immeasurable benefits to human health and the environment in the treatment of water and wastewater, but there are also negative environmental impacts and greenhouse gas emissions that until recently have been largely overlooked.

Greenhouse Gas Impact Estimation

Potable water is delivered to residential, commercial, and industrial customers within a geographical location from water municipalities. Most customers have become aware of the potential environmental burden and the resulting global warming effects associated with the water service activity. A need exists for the ability to estimate the carbon footprint associated with end users' water consumption, production and distribution. On the other hand, planners need to know the contribution of the water industry in greenhouse gas production (GHG) in order to establish a baseline for improved future operation. Water industry professionals lack a consistent tool and assessment methodology to estimate the GHG impact of water and wastewater operations. A carbon footprint assessment is a management tool that quantifies the potential environmental impact. It provides information for mitigation efforts to control and lower greenhouse gas emissions over time.

The current attempts to estimate the carbon footprint for the water industry entails complex process that examines all relevant activities that consume energy such as chemical production, transportation, and treatment processes. Although there are a dozen computer software programs that provide carbon footprint estimation for personal use and specific industries, none takes into account the total water system contributing elements and the associated geographical variants.

A cap and trade program may be implemented to reduce GHG emission. This type of program will require water industries to provide annual reports of their energy consumption and associated estimates of carbon emission. It is thus critical to develop a standardized method for estimating the GHG emissions associated with the municipal water cycle. A model can help decision makers in the evaluation of total system sustainability.

Hypothesis

A municipal water and wastewater service in a specific geographical region is indirectly responsible for the greenhouse gas emission attributed to the generation of electricity used in the distribution and treatment of the water. This carbon footprint can be quantified and estimated provided that the energy consumption for treatment, distribution and end use water demand are known. GIS is a tool for representing the embodied energy of water and geographical dependencies. The model must calculate the energy use per gallon supplied and the annual carbon footprint for each end user of water. This leads to deduce the following predictions regarding the water-energy nexus.

Hypothesis 1:

A GIS of the municipal water cycle can be developed and used to estimate the embodied energy of water at the demand side.

Hypothesis 2:

A GIS of the municipal water cycle can be developed and used to estimate the carbon footprint of water at the demand side.

Hypothesis 3:

A GIS of the municipal water cycle that estimates the embodied energy and carbon footprint and can support demand side sustainability planning such as zoning and facilities management.

Hypothesis 4:

A GIS of the municipal water cycle that estimates the embodied energy and carbon footprint, and that provides opportunity to identify business sectors which contribute significantly to the GHG emissions associated with water use.

Hypothesis 5:

A GIS of the municipal water cycle that estimates the embodied energy and carbon footprint as a viable tool to improve and expands sustainability rating systems such as LEED and Green Globes to include the water energy nexus.

Water and Energy

Water is indispensable to human health and well-being, and crucial for sustainable development. The sustainability of water systems however is not limited to the quality of the service provided. Approximately 4% of the nation's electricity goes towards moving and treating water and wastewater (Appelbaum, March 2002). There have been few studies published on the link between water use and the consumption of energy or emissions of greenhouse gases.

Water utilities and wastewater facilities require significant amounts of energy to collect, treat, and deliver drinking water; and to collect, treat, and dispose of wastewater. Consequently, municipalities are liable for the direct and indirect costs associated with the two systems. Direct costs are operational and utility costs measured in dollars and indirect costs include the environmental impacts associated with energy consumption. (Tripathi, April 2007) Energy use required for the consumption of potable water is directly linked to the emission of greenhouse gases. Most water is produced with non-renewable energy resources, and thus, the greater the embodied energy of water, the greater the emission of greenhouse gases (The-Brendel-Group, December 2007). Reduced consumption of electricity at treatment facilities means lower costs for municipalities and agencies responsible for their operations (Tripathi, April 2007). When energy consumption is reduced, embodied energy and the resulting carbon footprint are also reduced.

A system water cycle includes four major elements: water extraction and treatment, water distribution, wastewater collection, and wastewater treatment. Embodied energy refers to the quantity of energy required to manufacture, and supply to the point of use, a product, material or service. For the water utility sector, embodied energy is the total amount of energy associated with the use of a given amount of water in a specific location (Wilkinson, January 2000). It is the energy consumed by all the processes associated with the production, delivery, consumption, and disposal of water. For purposes of this research, the embodied energy will focus on the municipal energy consumption required for the production, delivery, and disposal of water in an urban water system. Embodied energy is typically expressed in watt hours per gallon of water (Wh/gallon). Embodied energy can be converted mathematically to a greenhouse gas emissions equivalent, typically a carbon dioxide emissions equivalent.

The United States Department of Energy (DOE) and the Environmental Protection Agency (EPA) has both initiated programs aimed at assessing the nexus between water and energy. Recently, DOE realized that there was a critical component missing from federally supported energy sustainability research and development. The missing piece was water and its interdependence with energy (DOE-Sandia-National-Lab, 2006). DOE, through the Energy-Water Nexus program, has been charged with developing technology products that will help increase the nation's energy and water security. The eleven national laboratories along with the Electric Power Research Institute (EPRI) are investigating energy usage by water-related systems and processes (Klein, November 2005).

EPA is also looking into the relationship between water and energy consumption. In a 2008 memorandum to EPA Regional Administrators, the Office of Water Assistant Administrator, Brian Grumbles, initiated further dialog on the nexus between water and energy by promoting energy efficiency for the water sector (Grumbles, 2008). Some of the Agency's efforts include adoption of environmental management systems (EMS), additions to the ENERGY STAR program to include water utility energy tracking tools and a carbon footprint calculator, and the use of Clean Water and Drinking Water State Revolving Funds to advance energy efficiency.

The EPA has also developed a step-by-step workbook to help utilities to ensure a sustainable future and is conducting workshops for water utility managers (EPA, An

Energy Management Guidebook for Wastewater and Water Utilities, 2008). In addition to federal agency efficiency and research initiatives with respect to water and energy, academic institutions have been considering the environmental and energy impacts of water treatment processes for a number of years. The current personal carbon footprint estimation tools do not incorporate the critical impact of topography and the end user geographical location. This research attempts to explore the importance of the geographical components.

Water System

A typical municipal water system consists of raw water extraction and treatment, potable water distribution, wastewater collection, and wastewater treatment and discharge. Figure 1 illustrates each of these elements in relation to the water user.

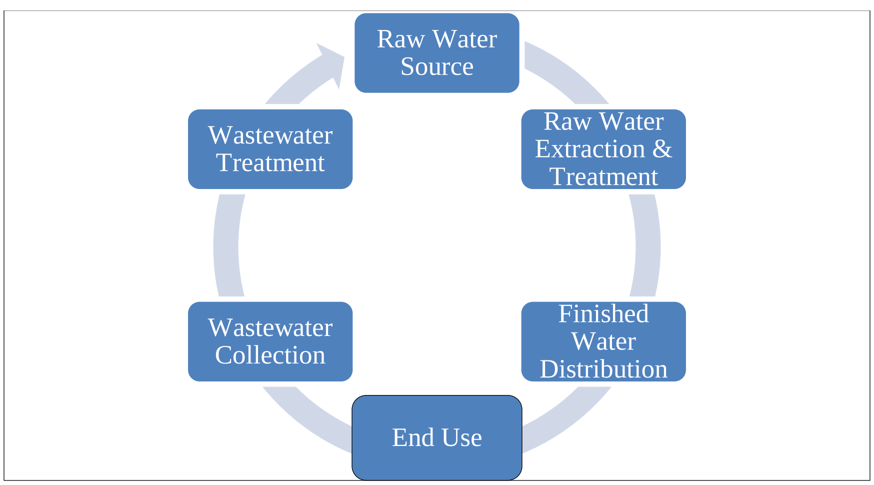

Figure 1: Recycling of Water in a Water System

Water Treatment

The first phase of a municipal water use cycle is diversion, collection, or extraction of raw water from a source (Klein, November 2005). For purposes of this research, water source extraction and treatment are regarded as the first element in a municipal total water system. Energy is required for the extraction of raw water from its source, either a surface water body or groundwater. Some water sources need very little treatment, so their energy intensity is low. Groundwater is naturally of higher quality than most surface water sources and requires less energy for treatment. However, the extraction of groundwater requires approximately 30% more electricity on a unit basis than from surface water extraction (Appelbaum, March 2002). The embodied energy required for source extraction is unique to every water system.

Once extracted, the water is treated to potable water quality standards. The energy required for treatment can vary widely and depends on source-water quality and treatment technologies. High quality groundwater may require little treatment and surface water taken from rivers that have upstream discharges of wastewater may require significant treatment (Cohen, Nelson, & Wolff, August 2004) resulting in higher energy demands. The embodied energy for every treatment plant is unique because water treatment processes vary considerably from system to system and from facility to facility. Reverse osmosis for example, provides a high level of treatment, but also uses large amounts of energy to maintain system pressure through the use of pumps (The-Brendel-

Group, December 2007). It is likely that energy use for water treatment will increase as more stringent water quality rules are implemented under the Safe Drinking Water Act and the Clean Water Act. Every source of water has different energy intensity (Klein, November 2005). Therefore, each water system needs to be evaluated on an individual basis to determine its embodied energy estimate and carbon footprint.

For purposes of this research, the actual treatment sequence will not be analyzed. The treatment plant's total energy consumption (for all operations) will be used as an input for the model calculations. Additional study could help determine the individual water treatment processes that contribute to higher or lower energy intensity when comparing one water system with another.

Table 1 represents the energy consumption of water treatment process components for a typical 10 MGD plant. For example, approximately 1,200 KWh/day is attributed to raw water pumping. It shows about 85% of the energy consumption in water treatment segment of water cycle is attributed to pumping treated water. (Appelbaum, March 2002)

Table 1: Daily Water Treatment Plant Energy Consumption for a 10 MGD Plant[1]

Water Treatment process	Energy Use KWh/Day	Percentage of total	Flow Million Gallons	Embodied Energy KWh/Mgal
Raw water pumping	1,205	8.4	10	1,426
Alum Addition	10	0.07		
Polymer Addition	47	0.3		
Rapid Mix	308	2.1		
Flocculation Basin	90	0.6		
Sedimentation Tanks	88	0.6		
Lime Addition	12	0.08		
Chlorine addition	2	0.01		
Filter Backwash Pump	123	0.8		
Filter Surface wash Pump	77	0.5		
Sludge Pump	40	0.2		
Decanted Wash water to Rapid Mix	200	1.4		
Treated Water Distribution	12,055	85		
Total Water Treatment	14,257	100		

Water Distribution

Once treated to potable water standards, water is distributed to customers through a network of storage tanks, pipes, and pumps. Some fresh water distribution systems can be gravity fed, but most require some pumping to maintain movement and pressure and to minimize corrosion and biological contamination (Klein, November 2005). The majority of energy consumed by municipal water systems is used for pumping, both at the extraction and treatment phase as well as the distribution phase. In most urban cases, energy is typically required for local pumping and pressurization requirements (Cohen, Nelson, & Wolff, August 2004). Because many urban water distribution systems were constructed underground more than 50 years ago, there is significant evidence that leaks and other infrastructure problems contribute the loss of potable water and resulting in

[1] Water & Sustainability, Vol. 4, The Next Half Century, Topical Report, March 2002

increased energy intensity for those systems. Aging infrastructure is not the single or most significant contributor to increased energy use for water distribution. The primary driver of increased energy use for water distribution is urban growth.

End Use

Water users consume energy by further treating, circulating, pressurizing, heating, or cooling delivered water (Cohen, Nelson, & Wolff, August 2004), or using energy intensive appliances for washing and showering. The focus of this research, however, is on the municipal water sector and the embodied energy required for the treatment and disposal of water delivered to the end user location. End user energy consumption to further heat the water, for example is not accounted for in the model.

Wastewater Collection

On the downstream side of a water system, energy is required to collect, pump, treat, and dispose of wastewater. Wastewater from urban uses is collected, treated, and discharged back to the environment, where it may become a source for someone else. A majority of conventional wastewater collection systems use gravity to convey wastewater to a treatment plant (Klein, November 2005). Wastewater collection system energy use is the most overlooked element of a water system. Most collection systems are gravity driven but there are many areas of urban water systems that require wastewater pumping and therefore contributing significantly to the embodied energy of delivered municipal water. These collection systems require energy to pump or lift the wastewater for treatment and discharge. Wastewater is collected and conveyed so that it can be delivered to the last element in the total water system, the wastewater treatment process.

Wastewater Treatment

Wastewater treatment plants require significant amounts of energy to remove impurities. Some require more energy than others depending on the quality of the waste stream, the level of treatment required, and the technologies employed by individual treatment plants (Klein, November 2005). Energy use is expected to increase as more stringent water quality rules are adopted. For purposes of this research, the wastewater treatment phase of a water system also encompasses the discharge of treated effluent to the environment. Depending on the plant location, effluent can be discharged by gravity or in some instances require energy for pumping to the environment.

Table 2 represents the energy consumption of wastewater treatment process components for a typical 10 MGD plant. For the purposes of this research, the actual treatment process will not be analyzed. Additional study could help determine the individual wastewater treatment processes that contribute to higher or lower energy intensity when comparing one water system with another and eventually process options.

Table 2: Daily Advanced Wastewater Treatment Energy Use for a 10 MGD Plant[2]

Advanced Wastewater Treatment Process	Energy Use KWh/Day	Percentage of total	Flow Million Gallons	Embodied Energy KWh/Mgal
Wastewater pumping	1,402	8.4	10	1,660
Bar screen	2	0.01		
Aired grit chamber	134	0.80		
Primary settling	155	0.93		
Aeration	5,320	32.04		
Nitrification	3,446	20.75		
Secondary settling	155	0.93		
Chemical mixer	552	3.33		
Filter feed	822	4.96		
Filtration	385	2.33		
Chlorination	27	0.17		
Flotation thickening	2,022	12.18		
Gravity thickening	25	0.16		
Aeration digestion	1,700	10.25		
Belt press dewatering	457	2.76		
Total	16,604	100		

While municipal water system research has been typically separated into potable water systems and wastewater systems, this research combines the embodied energy of water and wastewater treatments with the distribution or collection. The following literature review section provides examples of academic research that has studied the relationship between water and environmental impacts associated with energy consumption for all elements of the total water system.

[2] Water & Sustainability, Vol. 4, The Next Half Century, Topical Report, March 2002

CHAPTER 2- PRIOR RESEARCH

Previous studies have evaluated and modeled the life cycle energy and greenhouse gas emissions associated with water treatment, wastewater treatment, piping, pumping, and end users. The results of the literature review showed the water-energy nexus to be of global concern. The research work reviewed hereon provides case studies for water and wastewater systems throughout the world including Sweden, Taiwan, and South Africa.

Water Treatment

A recent study by (Racoviceanu, Karney, Kennedy, & Colombo, December 2007) aimed to quantify the total energy use and greenhouse gas (GHG) emissions for a conventional water treatment system in North America. Using a life-cycle approach, the study considered three phase processes for water treatment systems which included chemical production, chemical/material transportation, and treatment plant operation. The authors noted that this is one of few studies to contemplate the life cycle energy and GHG emissions in North American water treatment systems. Few studies have focused on the performance of Water Treatment Systems in recognition of rising concerns over scarce energy resources and global climate change. The authors suggested that further study of more complex urban water systems (water distribution and wastewater collection and treatment) would be beneficial to highlighting the relative importance of upstream and downstream energy consumption associated with water use.

The environmental burden created by the production of potable water based on a Life Cycle Assessment (LCA) methodology was calculated. (Frieddrich, 2001) The study compared two methods (conventional and membrane) used in the production of potable water in South Africa. The LCA included a life cycle inventory of inputs and outputs for each phase of the potable water production process and a life cycle analysis to define burdens and impacts created by the inputs and outputs processes. The environmental impact categories considered for this study were global warming, ozone depletion, acidification, nitrification, photochemical oxidant formation, and ecotoxicity and human toxicity. A conventional method of water treatment and eight design scenarios for the membrane method were evaluated. The majority of environmental burdens were traced to one single process, the generation of electricity in South African coal power plants. For the conventional method, the ozonation and sludge disposal processes were the most energy intensive processes and therefore carried the greatest environmental burden. For the membrane method, the design option with the lowest electricity consumption had the lowest environmental impact. Because the membrane method required the most energy, its global warming potential was comparatively higher than the conventional method.

Water Distribution

A life cycle energy analysis (LCEA) of a water distribution system was presented (Filion, MacLean, & Karney, Septemeber 2004). The authors recognized the need for sustainable infrastructure for water-distribution networks. Urban populations rely heavily on water distribution networks to provide potable water to perform basic domestic activities. The networks provide water during fire emergencies and support commercial and industrial activities. The life cycle included the fabrication, use, and end-of life stages of the pipes of a water distribution system. While other studies have explored the life-cycle cost and life-cycle environmental impacts of civil infrastructure systems, this study was believed to be the first of its kind to deal with the energy expenditures incurred in all life stages of a water distribution system. The New York primary water supply was used as an example to show the energy expenditures associated with four planning scenarios. The four scenarios represented possible pipe-replacement schedules for 10, 20, 50, and 100 years. The results indicated that the energy required to fabricate pipes for replacement was the most energy intensive of the life-cycle phases. Energy requirements for pumping increased with longer replacement periods because of the higher pumping demands associated with aging infrastructure. However, replacement energy was orders of magnitude higher than other factors (i.e. Pumping operations) and the results suggested that pipe replacement period should be around 50 years.

Wastewater Treatment

The differences in the environmental loads imposed by conventional wastewater treatment processes with that of separation systems in Northern Sweden were presented. (Lundin, Bengtsson, & Molander, Life Cycle Assessment of Wastewater Systems, 2000) The authors recognized the need for long-term ecological sustainability of urban water systems that move beyond the protection of human health and receiving waters. The focus was on minimization of resource use and reduction of energy and water use. Two case studies of conventional wastewater systems were chosen to make a comparison between large-scale and small-scale wastewater treatment systems. A Life Cycle Inventory was used to compare the environmental loads from wastewater systems with different technical solutions, conventional and separation. The environmental loads included in the inventory analysis were energy and materials use, emissions to air, emissions to water, and waste generation. To calculate the environmental load of energy use, the average Swedish mix of 49% nuclear, 44% hydropower, and 7% combined power and heating plants was used. For the system operation phase, electricity demand per functional unit for small-scale systems was found to be four times higher than that of large-scale systems. However, the authors concluded that separation systems reduced the need for production of mineral fertilizers and thus reduced overall use of energy. Separation systems used in conjunction with conventional treatment, consumed less energy than if all wastewater was treated conventionally.

Researchers in the Netherlands and Germany (Balkema, Preisig, Otterpohl, & Lambert, 2002) questioned the sustainability of urban wastewater treatment systems and the need to improve to existing systems or switch to decentralized systems. The authors conducted an extensive literature review and summarized current sustainability assessment methods and currently used indicators. There were multiple objectives in the optimization of wastewater treatment systems, and the study sought to identify the general assessment methodology that uses a multi-criteria assessment for the sustainability of municipal wastewater treatment systems.

Looking at a specific treatment process, (Shizas & Bagley, August 2004) sought to evaluate the potential for anaerobic waste treatment to produce renewable energy resources such as methane and hydrogen. This study claimed to be first to look at municipal wastewater, whereas other studies have measured the energy content of municipal solid waste. The goal was to create an energy balance for the entire treatment plant by measuring the energy content of wastewater. The results of this study showed that the energy content of raw municipal wastewater and wastewater treatment sludge using available methods. There was also the potential for energy in the wastewater to exceed the requirements of the facility using appropriate technologies. With further study, municipal wastewater treatment plants could have the potential to become net producers of renewable energy.

Total Water System

A procedure for assessing the environmental sustainability of urban water systems was presented. (Lundin & Morrison, A Life Cycle Assessment Based Procedure for Developement of Environmental Sustainability Indicators for Urban Water Systems, Feburary 2002) Due to the complexity of life cycle assessments, the authors identified the need for less complicated methods and presented a procedure for assessing the environmental sustainability of urban water systems through the use of carefully developed Environmental Sustainability Indicators (ESI). The purpose of this study was to assess the environmental sustainability of the urban water system in order to support and improve decision-making at the water company level. They defined the system boundaries for the urban water system, starting with the withdrawal of water from groundwater or surface water and also included drinking water and wastewater treatment. The life cycle ended with the discharge of treated wastewater to the aquatic ecosystem and disposal of sludge.

The case study water systems were located in Sweden and South Africa. The life cycle of the urban system case studies were divided into four environmental and technical systems. The four systems were (1) withdrawal of freshwater, (2) production, distribution and use of drinking water, (3) collection and treatment of wastewater, and (4) handling of by-products such as sludge, biogas and heat. Chemical and energy uses were evaluated as environmental sustainability indicators for treatment purposes. The authors defined the most important ESIs for urban water systems. The authors recommended that electricity use for water supply and for wastewater treatment be used as an ESI for assessing the environmental sustainability of an urban water system.

(Lundie, Peters, & Beavis, 2004), were the first to create an LCA model that integrated the sustainability assessment of both water and wastewater systems. The model was developed to serve as a planning tool for the examination of alternative future water system scenarios. A case study was applied for a water system in Sydney, Australia. This study developed an LCA consistent with the ISO framework 14040. A wide range of environmental indicator categories were developed including total energy, climate change, and a variety of water quality indicators. Schematically, the model encompassed an entire city's water system, beginning with bulk water supplies to water filtration plants, water system areas, customer areas, wastewater systems areas, and sewage treatment plants. Applying the methodology to Sydney's Australia's water system, the LCA was intended to show which aspects of the water business placed the largest burdens on the environment. The LCA became significantly complex compared to previous studies because water delivery systems and sewage catchments did not always share common boundaries in Sydney. Several geographical sub areas had to be modeled.

For the environmental indicator, energy consumption, a Life Cycle Inventory (LCI) analysis was used to calculate the total material and energy flows for the entire system. Because data quality for energy use was high, identification of fixed and variable (pumping) components for each unit and area in the Sydney system was inventoried. The authors investigated several scenarios to compare overall environmental performance for system alternatives. Examples of the scenarios include four alternative population estimates for Sydney, improved energy efficiency for infrastructure and lighting, and increased energy generation opportunities. Initiatives considered in the energy efficiency scenario saw the greatest saving in energy consumption (13%) and GHG emissions. The study concluded that the LCA methodology was successfully applied to the planning process for the overall business of Sydney Water. LCA provided a defensible methodological platform on which to quantify environmental burdens for a baseline and for future alternatives.

Cheng presented an overview of residential water use and associated electrical energy consumption requirements for residential applications. (Cheng, May 2002) The author collected energy consumption data for water and wastewater supply and treatment systems in Taipei, Taiwan. From the data, the author was able to deduce an average energy consumption (kWh) per unit of residential water (cubic meter) for end user systems (pumping and heating), municipal water supply systems (treatment and distribution), and municipal wastewater treatment systems.

Wilkinson examined the energy intensity of water used in specific geographic areas in the state of California. (Wilkinson, January 2000) California's water systems relative to national averages are uniquely energy intensive due to the pumping systems used to convey water in large volumes over long distances and elevations. Water systems in

California account for one of the largest energy uses in the state, estimated to be about 6.9% of the state's electricity.

A methodology was developed that accounted for all of the energy requirements associated with water used within a specific service area. Total embodied energy for the purposes of this study included energy inputs for local treatment and distribution, end user requirements, and wastewater collection and treatment. To apply the methodology, the author developed a spreadsheet tool with equations imbedded that calculated the total energy requirements for water use. The author suggested that the spreadsheet could be linked directly to GIS applications, so that data could be calculated and displayed for a user.

The study found that the energy intensity of water varies considerably by end user geographic location and the water source. The paper identified opportunities for efficiency improvements in water management such as better operations management and incorporation of technological changes. It was predicted that energy intensity will increase as water resources are further limited and regulatory requirements for water quality become more stringent. The study also provided background information, references, and sources to facilitate further research in water system energy use.

Tripathi documented the energy intensity and environmental impacts of water and wastewater treatment operations through case study evaluations of water and wastewater treatment facilities. (Tripathi, April 2007) Four case-studies, three wastewater plants and one water treatment plant, were used to characterize the amounts of energy and emissions for such facilities. Data obtained from both Ann Arbor, Michigan water treatment plant and the wastewater treatment plant was analyzed to establish the total energy consumed by water and wastewater systems. The life-cycle assessment was restricted to operation of the plants and pumping stations, production of chemicals required for treatment, fuels used at the plants, and fuels used for disposal of sludge.   The total life-cycle energy in Giga joules per million gallons of water required for each plant operation was calculated. The emissions generated due to the operations were also categorized into global warming potential or kg CO_2 eq. /Mgal.

The study found that annual electricity consumption at the water treatment plant was lower than that of the wastewater treatment plant.   However, the energy consumption in the form of treatment chemicals and natural gas use contributed to higher total life-cycle energy for the Ann Arbor water treatment plant than the wastewater treatment plant. Because overall energy consumption was higher for the water treatment plant, so were the carbon dioxide equivalent emissions. The author noted that presently available literature and research focused on water treatment plants and wastewater treatment plants as individual systems while their interdependence is significant enough to warrant study of the entire system. The study concluded that this type of research is crucial for the development of sustainable strategies.

A result of a survey of energy consumption per unit of water for the nation's water and wastewater treatment plants is shown in Table 3. Another study of embodied energy was conducted for seven municipalities in Ontario, Canada. (Mass, 2009) It estimated embodied energy for large water cycle systems to be 2.6 MWh/Mgal. Table 4 shows a summary of the Canadian results.

The impact of elevation on the consumption of energy to distribute water to buildings was investigated in a case study. (deMonsabert, Bakhshi, & Headley, Embodied Energy in Municipal Water and Wastewater, June 2008) The study recommended development of a GIS based model to account for the emission and the embodied energy of a total water system and the associated consumption by end use.

Table 3: US Mean Results- EPRI[3]

	Treatment Plant size	**Unit Energy Consumption – MWh/Mgal**	
		Advanced Wastewater Treatment with (Nitrification)	**Surface Water Treatment**
National	10 MGD	1.79	1.406
National	50 MGD	1.59	1.408
National	100 MGD	1.56	1.407

[3] Electric Power Research Institute: Water & Sustainability, Vol. 4, The Next Half Century, Topical Report, March 2002

Table 4: Mean Embodied Energy, Ontario Canada

Water Use Component	Mean Energy Intensity MWh/Mgal (kWh/m3)			
	Surface Supply (WTPs)		Groundwater Supply (Wells)	
	Small Capacity < 1.3 MGPD (< 5,000 m3/d)	Large Capacity > 1.3 MGPD (> 5,000 m3/d)	Small Capacity < 0.3 MGPD (< 1,000 m3/d)	Large Capacity > 0.3 MGPD (> 5,000 m3/d)
Water Treatment & Source Extraction[4]	3.0 (0.80)	1.5 (0.41)	2.8 (0.74)	1.78 (0.47)
Water Distribution	0.64 (0.17)	0.64 (0.17)	0.64 (0.17)	0.64 (0.17)
Water Sub-Total	3.7 (0.97)	2.2 (0.58)	3.4 (0.91)	2.4 (0.64)
Wastewater Treatment	0.32 (0.085)	0.14 (0.036)	0.32 (0.085)	0.14 (0.036)
Wastewater Collection	0.23 (0.06)	0.23 (0.06)	0.23 (0.06)	0.23 (0.06)
Wastewater Sub-total	0.53 (0.14)	0.38 (0.10)	0.53 (0.14)	0.38 (0.10)
Total Energy Intensity	4.2 (1.11)	2.6 (0.68)	4.0 (1.05)	2.8 (0.74)

Sustainability Rating Systems

While there are various online tools and models for determining personal carbon footprint and environmental impacts, there are a growing number of on-line tools aimed at assessing the climate change impacts of larger organizations. There are a variety of sustainability rating systems available to all sectors of business and industries. These sustainability rating systems often evaluate the greenhouse gas emissions associated with the operations of various sectors. Greenhouse gas emissions calculators have been developed to estimate the carbon footprint for homes and offices and other energy consuming practices such as transportation resources. These calculators can be used by organizations and institutions to assess organizational sustainability by comparing and

[4] Includes source extraction, treatment and in some cases a portion of high lift pumping

evaluating environmental indicators like carbon footprint. Organizations in the commercial, industrial, government, and education sectors can use sustainability indicators for planning purposes, comparisons with similar organizations, or benchmarking to establish energy efficiency or footprint reduction goals. The information provided below briefly describes some readily available sustainability assessment tools and rating systems and carbon footprint calculators. Those included are rating systems and tools aimed at universities, green building practices, and most recently, wastewater treatment plants.

STARS

Established by the Association for the Advancement of Sustainability in Higher Education (AASHE), the Sustainability Tracking, Assessment, and Rating System for colleges and universities was developed to allow higher learning institutions to gauge progress toward sustainability (STARS, 2009) The program aims to create a standard and comprehensive way for colleges and universities to compare sustainability and benchmark individual institution's performance over time. The STARS rating system provides a transparent process for ratings. It incorporates and encourages participation from community colleges and research universities alike. STARS was designed to: (1) Provide a guide for advancing sustainability in all sectors of higher education, (2) Enable meaningful comparisons over time and across institutions by establishing a common standard of measurement for sustainability in higher education, (3) Create incentives for continual improvement toward sustainability, (4) Facilitate information sharing about higher education sustainability practices and performance, and (5) Build a stronger, more diverse campus sustainability community. Colleges and universities can earn STARS credits in three categories: Education and Research, Operations, and Administration and Finance. Operations credits however can be earned for greenhouse gas (GHG) reductions. The STARS guidance recognizes GHG inventory methodology consistent with the Greenhouse Gas Protocol's Corporate Accounting and Reporting Standards described below.

Greenhouse Gas Protocol Initiative

The Greenhouse Gas Protocol Initiative's GHG Protocol is the most widely used international accounting tool for business and government leaders to understand, quantify, and manage greenhouse gas emissions. (GHG-Protocol, 2001) The Corporate Standard provides guidance and standards for companies preparing a GHG inventory. The Initiative also has a wide variety of Calculation Tools available online for calculating greenhouse gas emissions for a variety of business sectors. Although industry-specific, the calculation tools can be applied by NGOs, government agencies, and universities. Sector toolsets are available for all types of industry, from acid production to wood products. There is also a suite of toolsets aimed at the office and service sector. Excel spreadsheets can be accessed that calculate direct and indirect emissions. Direct emissions are emission sources owned or controlled by the company like the burning of fuel oils. Indirect emissions are those emissions from use of purchased electricity, heat or steam. Other indirect sources which emissions can be calculated include commuting, business travel, and mobile sources.

Clean Air Cool Plant

This is another example of a rating system developed for university sustainability assessment. Clean-Air Cool Planet is an organization dedicated to finding and promoting solutions to climate change. It supports educational institutions in finding and demonstrating energy and global warming solutions through their Campus for Climate Action program. Like the STARS rating system, Clean-Air Cool Planet has established a program and published a Campus Climate Action Toolkit which includes a greenhouse gas emissions inventory calculator for campuses across North America (CA-CP, 2008). The toolkit also provides a practical framework for campus climate change leadership action, technical resources, and case studies. Campuses located in the northeast region of the country are invited to use this online tool to track individual environmental footprints and make comparisons to other colleges and universities.

LEED

The most commonly used green building rating system was developed by the U.S. Green Building Council (USGBC). USGBC has recognized that in the United States, buildings use one-third of the nation's total energy, two-thirds of the nation's electricity, and one-eighth of the nation's water, and transform land that provides valuable ecological resources (USGBC, 2005). Developed by USGBC, the Leadership in Energy and Environmental Design (LEED) for New Construction (NC) Rating System is designed to guide and distinguish high-performance commercial and institutional projects, including office buildings, high-rise residential buildings, government buildings, recreational facilities, manufacturing plants and laboratories. The current NC Version 2.2 rating system is organized into five environmental categories including Sustainable Site, Water Efficiency, Energy and Atmosphere, Materials and Resources, and Indoor Environmental Quality. Credits are earned for each green building practice incorporated into the building design and construction operations and the ultimate goal is to reduce the impact of buildings on the environment.

ENERGY STAR for Wastewater Plants and Drinking Water Systems

The U.S. Environmental Protection Agency through its ENEGY STAR program has established an interactive energy management tool called Portfolio Manager. This tool can be used by a variety of commercial building applications like hospitals, retail spaces, and specifically wastewater treatment facilities. Portfolio Manager helps wastewater system managers track and assess energy and water consumption across their entire portfolio (ENERGY-STAR, 2008). Once the manager has entered energy consumption and cost data into the Portfolio Manager account, they can begin to benchmark building energy performance, assess energy management goals over time, and identify strategic opportunities for savings and recognition opportunities.

Wastewater treatment facilities are considered to be a part of the commercial building market and are eligible for Portfolio Manager tracking and ENERGY STAR rating. The EPA energy performance rating system is based on source energy and accounts for weather impact variations as well as key physical and operating characteristics of the facility. Wastewater treatment managers are able to track energy use, energy cost, and associated carbon emissions. Used as an energy performance rating system, Portfolio Manager currently allows wastewater treatment plant managers to compare the energy use of their plants with other peer plants. Portfolio Manager is appropriate for primary, secondary, and advanced treatment facilities with or without nutrient removal and is best applied to facilities of 150 MGD or smaller. Portfolio Manager currently does not apply to water treatment and distribution facilities. The Portfolio Manager for wastewater treatment plants is a first step in evaluating the energy consumption and carbon footprint associated with the water utility sector. However there is still a gap in the analysis of the water utility sector as a whole.

GIS Modeling

Hydraulic software modeling tools for water distribution are used to estimate power consumption of pumps and other related water infrastructure components. Water distribution is one components of municipal water cycle that can be modeled.

In one case study, an application of the theoretical hydraulic formulas using a GIS framework for estimation of the energy consumption attributed to pumping of wastewater was tested. (deMonsabert & Bakhshi, A GIS Methodology for Estimating the Carbon Footprint in Municipal Water and Wastewater in Fairfax County, September 2009) The estimation highly depends on the quality of the GIS dataset. Due to inaccuracies and omission of underlying attributes of a given utility company GIS dataset, the margin of error was high. Use of hydraulic formulas could not take into consideration 1) The energy consumption attributed to stations lighting, and heating, ventilating of buildings; 2) Absence of a hydraulic model calibration on existing water piping network; 3) Absence of meters at pump stations to measure run-time.

GIS could be used to complement the water distribution modeling. In one study, a GIS enabled software (H2OMAP) was introduced as a decision support system. It allows network improvement and enhancement alternatives to a modeled system. (Ennis, Boulos, Heath, & Hauffen, 2001)

Software developers have recently expanded their water industry products into sustainability assessment extension. As an example, MWH Soft promised to release a water network Sustainability Analysis extension to its lines of products. It claimed that the model would be able to determine the carbon footprint for pumps and the cumulative total energy lost across all elements in a water distribution network, from source to end use tap. (MWH-Soft, 2009)

A water distribution model involves the spatial allocation of customer water demand. Using GIS spatial analysis, demand density can be determined for a specified geographical area. One factor that affects demand allocation is population growth in a service area. In another study, three different methods of water projection were analyzed in terms of population growth (gpd/person), land use or area method (gpm/acre), and point based method (customer billing records) for the city of Olathe Kansas. (Baumberger, Hart, & Darkwah, December 2007)

Literature Review Summery

The reviewed literature emphasized the life cycle assessment of water and wastewater treatment processes. While many researchers recommended energy consumption as a sustainability indicator for water supply and wastewater treatment systems, there is a gap in the analysis of total water system energy use contributing to the carbon footprint of water utilities. Determination of embodied energy for a whole cycle can account for not only the energy consumption due to treatment processes, and pumping, but also entail energy for extraction of resources and fabrication of materials, chemicals, infrastructure construction, transportation of materials to the treatment plants, and even employee commute to run the treatment operation. It is thus important to narrow the research to those elements that data is readily available and that are considered the most energy intensive factors in a water cycle. GIS tools have been used as a complementary tool to model water distribution. However, there is a gap in the literature that allow for the spatial analysis of the carbon footprint associated with the water-energy nexus.

A critical factor that is missing in past research is the use of a consistent and reliable metric to evaluate and estimate the GHG impact associated with a total water cycle and inclusion of end user level of consumption. This metric depends on the amount of water consumption by customer, the level of water treatment required in a geographical region, the location of customer in terms of elevation, and distance relative to the treatment plants within a water service boundary, and the availability of a viable model for estimation.

Application of GIS software seems to be a promising tool that could provide an opportunity to not only visually observe the customers’ embodied energy and GHG impact within a geographical location, but also the ability to improve the water and wastewater planning.

CHAPTER 3- CARBON FOOTPRINT CONCEPT

The carbon footprint associated with the whole water system is currently not measured, modeled, or evaluated by any observed analysis. What is the climate change contribution associated with the embodied energy in municipal water and wastewater systems? How significant is the carbon footprint of water and wastewater distribution, treatment and collection? Many of the aforementioned rating systems focus on the energy consumed by appliances, vehicular use, lighting, heating and air conditioning. How does the carbon footprint of embodied energy in water and wastewater compare with some of the other well studied energy consumers? Should a carbon footprint model be developed that incorporates the embodied energy from a total water system perspective? To answer these questions, the carbon footprint contribution was estimated for a variety of system configurations. (deMonsabert, Bakhshi, & Headley, Embodied Energy in Municipal Water and Wastewater, June 2008) The case studies were conservative with regard to energy consumption. A relatively flat terrain was investigated; similarly, facilities were located within five mile proximity of the wastewater and water treatment plants. Once the carbon footprint of the embodied energy was calculated, it was compared with the carbon footprints of other energy consumer appliances.

Systems diagrams shown in Figures 2 and 3 illustrate the elements that contribute to the embodied energy and the associated carbon dioxide emissions associated with a gallon of delivered municipal water to end user.

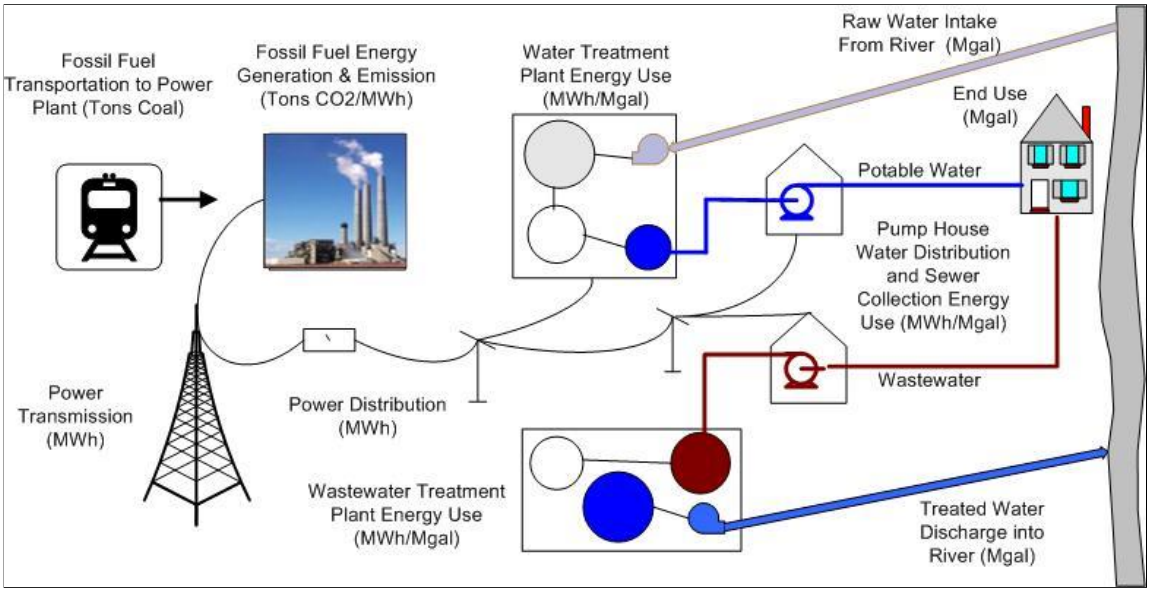

Figure 2: Overview of Water Use and Electric Energy Consumption

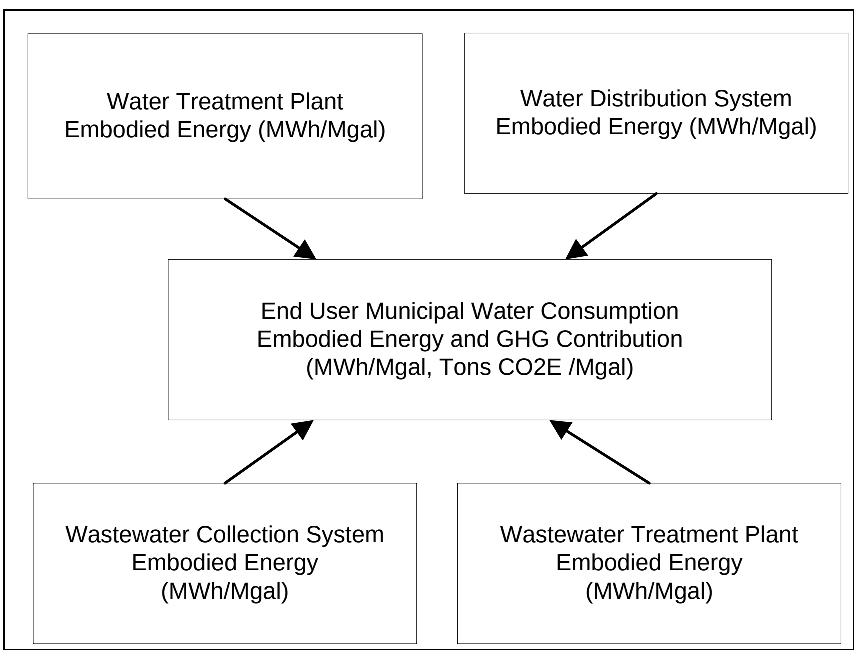

Figure 3: Flow Diagram of Energy Inputs to Water System

In one case study, a simple spreadsheet was developed to estimate the embodied energy of water for two residential users. Water and wastewater treatment energy consumptions were based upon a 2002 EPRI study. The embodied energy factor was extracted from a DOE study (Appelbaum, March 2002). The energy losses for the distribution and the collection systems were calculated based on the Hazen Williams formula and the following assumptions:

- Elevations of the two residential water users (50 ft, 250 ft)
- Elevation of the water treatment plant (0 ft)
- Elevation of the wastewater treatment plant (100 ft)
- Distribution piping is 4 inches in diameter and has a C factor of 100
- House pressure is maintained at 60 psi
- Houses are both 5 miles from both water and wastewater treatment plants
- Average daily demand for each house is 350 gal/day, and
- Pump and motor efficiencies are 90% and 95% respectively

As expected, even for a relatively flat terrain (elevation difference 200 feet) the embodied energy resulting from water distribution pumping varies considerably. Table 5 shows the results for the first simulation (WTP elevation: 0 ft, WWTP elevation: 100 ft, residential elevation: 50 ft). It also shows the results for the second model (WTP elevation: 0 ft, WWTP elevation: 100 ft, residential elevation: 250 ft). Wastewater for residence 2 is delivered by gravity thus no energy is consumed for its collection.

Table 5: GHG Analysis of two hypothetical residences in US [5]

Water System Segment	Embodied Energy (kWh/gal)	House Demand (gal/day)	Energy Use/Day (kWh/day)	Energy Use/ Day (kWh/year)	Emission Intensity lbs CO_2/kWh kg CO_2/kWh)	CO_2 Emissions per year lbs CO_2/year (kg CO_2/year)
Water Treatment	0.001406	350	0.4921	179.62	1.16 (0.53)	208 (94)
Wastewater Treatment	0.001911	350	0.66885	244.13	1.16 (0.53)	283 (128)
Water Distribution (Pumping)	0.000764 [1] 0.001500 [2]	350	0.2674 [1] 0.5250 [2]	97.60 [1] 191.63 [2]	1.16 (0.53)	113 (51) [1] 222 (101) [2]
Wastewater Collection	0.0001960 [1] 0.0 [2]	350	0.06860 [1] 0.0 [2]	25.04 [1] 0.0 [2]	1.16 (0.53)	29 (13) [1] 0.0 [2]
					Total	**633 (288) [1] 713 (323) [2]**

It is evident from the case study that the embodied energy and carbon footprint of municipal water can vary considerably by geographic location. A change in elevation of 200 feet in this case increases the CO_2 emissions by 12.6 percent. This includes not only the geographic location of the end user but also of the location of water treatment plant and wastewater treatment plants. In both residences, the estimated carbon footprint of the embodied energy for water use was greater than 630 lbs CO_2/year (285 kg/yr). How does this figure compare with other residential energy-uses? Table 6 shows the approximate carbon emissions for a variety of residential appliances, assuming the residences are located in Virginia (carbon conversion factor of 1.16 lb CO_2/kWh or 0.53 kg CO_2/kWh). Even with a small difference in elevation between the water treatment plant and the end-user (50 ft, 15 m), the GHG impact for water and wastewater is greater than most common residential appliances. Of the appliances studied, compact florescent lighting

[5] Note: Brackets represent the results for two scenarios

fixtures (CFL type) had the higher CO_2 emissions after emission level of water and wastewater industries. This comparison suggests that the magnitude of embodied energy is significant when compared with other energy consuming appliances.

Table 6: Residential Energy Consumption and Carbon Footprint Estimates [6]

Appliance	Use Assumptions	KWh/use	KWh/year	GHG Emissions per year lbs CO2/year (kg CO2/year)
Microwave Oven	96 times per year	0.945 kWh per use (based on 1.39 kWh for full power and 0.5 kWh for defrosting)	90.72	105 (48)
Washing Machine	187 washes per year	EU energy label A-rated gives an average consumption at 40°C using a 2kg load to be 0.63 kWh	117.81	137 (62)
Electric Tumble Dryer	148 uses per year	2.50 kWh per cycle	370.00	105 (48)
Electric Oven	135.1 uses per year	1.56 kWh per use	210.76	244 (111)
Dishwasher at 65°C	135 uses per year	1.44 kWh per use	194.40	226 (103)
Fridge-Freezer A spec	24 hours a day	408 kWh per year	408.00	473 (215)
Personal computer	365 days a year	270 w x 2 hrs per use	197.10	229 (104)
CFL Light Bulbs; assume 15 bulbs	4 hours a day	20 W [7]	438 [8]	508 (230)

[6] Source: http://www.carbonfootprint.com/energyconsumption.html
[7] 20W CFL is equivalent to 75W incandescent bulb: http://media.popularmechanics.com/documents/compact-fluorescent-test-0507.pdf
[8] http://www.energystar.gov/ia/partners/promotions/change_light/downloads/bulb.html

CHAPTER 4- OBJECTIVE AND METHODOLOGY

Objective

The purpose of this research is to estimate the greenhouse gas impact namely carbon dioxide emission of municipal water consuming customers that are associated with the four sub-systems of municipal water and wastewater serving a specific region. It is also attempted to include all the geographically variant elements in determination of this environmental indicator. Determination, mapping, and impact analysis of the end use embodied energy of consumed water and thus the attributed indirect carbon emission level in a region is desired.

Methodology

The embodied energy and emission parameters depend on the amount of water consumption by customer, the level of water treatment required in a geographical region, the location of customer in terms of elevation, and distance relative to the treatment plants within a water service boundary. To meet the research objective, the ArcGIS Desktop 9.2 was selected as the tool to devise the carbon footprint estimation model. (ESRI, 2008) The following factors are considered:

- Water treatment energy consumption based on electrical utility records
- Water distribution energy based on pump station electric meter readings
- Wastewater treatment energy consumption based on electrical utility records
- Sewage collection energy based on lift station electric meter readings

Energy consumption data for the four sub-systems is generally not readily available; however previous studies have shown this embodied energy to be significant. (deMonsabert, Bakhshi, & Headley, Embodied Energy in Municipal Water and Wastewater, June 2008)

The following describes further the theory, and methodology undertaken for this research. Chapter 5 describes the overall approach for the development of the GIS model.

Governing Hydraulic Equations

The power requirement for pumping of water or sewer along the distribution piping can be estimated from Bernoulli's equation. The hydraulic power, (Bhp) used to lift water H feet at a rate of Q (gpm) can be determined as follows:

$$\mathrm{Bhp} = \frac{\mathrm{Q} \times \mathrm{H} \times \mathrm{Sg}}{3{,}960 \times \mu} \qquad \text{(Eq. 1)}$$

Where:

Bhp = Hydraulic Power, or Brake Horsepower
Q = Flow rate, gpm
Sg = Specific gravity of water (=1 @ 60 deg. F)
H = Head height, ft
μ = Pump efficiency

In a hydraulic system, a fluid possesses energy in three forms, kinetic energy, potential energy and pressure energy. (Walski, Chase, & Savic, 2001) The pumping head to push water through a system of pipes and valves must consider static head, pressure head, and the head attributed to all losses due to friction. This is based on the Bernoulli's theorem for conservation of energy as it is applied to a flowing liquid; the equation is applied to two points (Point i and Point o) as illustrated in Figure 4. (Hauser, 1996)

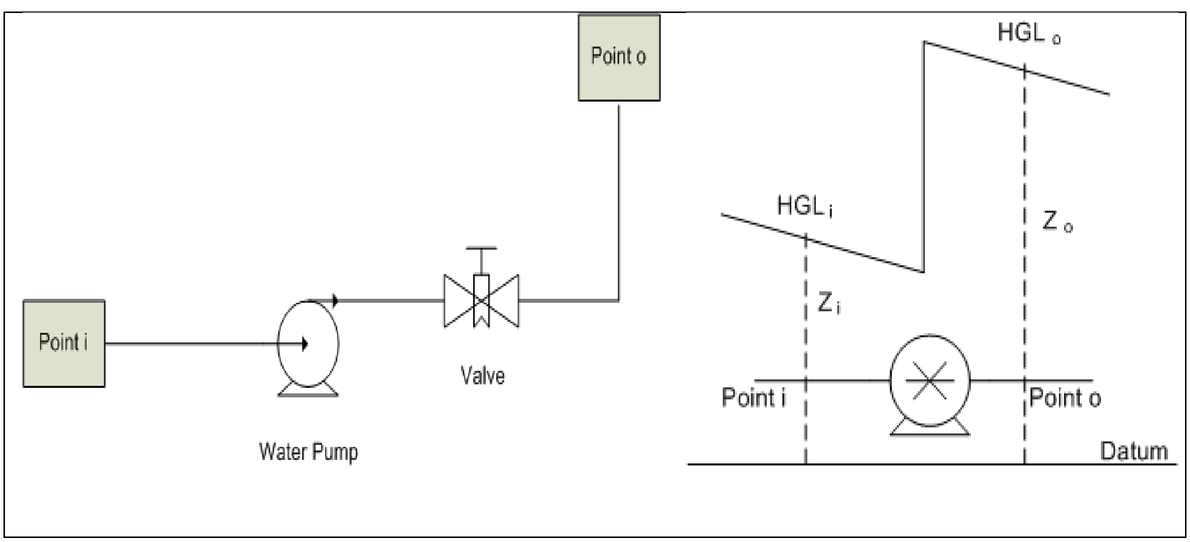

Figure 4: A Pipe System Diagram and Fluid's Energy in a hydraulic system

$$[Z + \frac{P}{\gamma} + \frac{V^2}{2g}]_i + H_p = [Z + \frac{P}{\gamma} + \frac{V^2}{2g}]_0 + H_{loss} \qquad \text{(Eq. 2)}$$

Where:

Z= Static head (ft)
P= Pressure (lbs/ft^2)
γ = Specific Weight (lbs/ft^3); water at 39 degrees Fahrenheit is 62.4 lb/ft^3
V= Velocity (ft/sec)
g = Gravitational acceleration, 32.3 (ft/sec^2)
H_p= Pump head (ft)
H_{loss} = Friction and other losses (ft)
HGL= Hydraulic Grade Line (ft)

The friction loss can be estimated using the Hazen-Williams equation:

$$H_{loss} = 0.002083 \times Leq \times [\frac{100}{C}]^{1.85} \times [\frac{Q^{1.85}}{d^{4.8655}}] \qquad \text{(Eq. 3)}$$

Where:

L_{eq} = Equivalent length of pipe and fittings (ft)
d = Inside diameter (in)
C= Hazen-Williams friction factor
Q= Flow rate (gpm)
L_{eq} is assumed to equal 1.5 times the pipe length and C is assumed to equal 100.

The electrical power EP (kWh) input to a pump motor can be determined from the Brake Horsepower using the motor efficiency, ε and the operating hours as shown:

$$EP = \frac{0.746 \times \text{Bhp}}{\epsilon} \qquad \text{(Eq. 4)}$$

Where:

EP= Electrical Power input to motor (KWh)
Bhp= Brake Horsepower (barrels- 42 gal per hour)
ε = Motor efficiency

The energy of fluid per unit of weight of the fluid for each point in the system is the fluid head. A Hydraulic Grade Line (Fig. 4) is an energy profile diagram for a pipe line. It is a plotted line for the sum of elevation head (potential energy) and pressure head (pressure energy) versus distance through a hydraulic system. The pressure in a pipe at any point then can be determined knowing the HGL:

$$P = \gamma \times (HGL - Z) \qquad \text{(Eq. 5)}$$

Where:

P = Water Pressure (lb/ft^2)
γ = Fluid Specific Weight (lb/ft^3)
HGL = Hydraulic Grade Line (Feet)
Z = Elevation above datum (Feet)

Water pressure is created by pumping water through a distribution system. A service area is typically divided into several "pressure zones" according to the elevation of a neighborhood. Typical standard for water pressure is between 50-100 psi. The water pressure at a customer depends on the elevation and proximity to the water storage source.

The minimum Hydraulic Grade Line for a distribution zone is determined to serve the customers located in the highest elevation within a pressure zone (Walski, Chase, & Savic, 2001):

$$\mathrm{HGL} > HE + 2.31\,\frac{\mathrm{ft}}{\mathrm{psi}} \times \mathrm{MP} \qquad \text{(Eq. 6)}$$

Where:

HGL= Hydraulic Grade Line (Feet)
HE= Highest Elevation (Feet)
MP= minimum Pressure (Psi)

The hydraulic formulas were used to estimate the energy required to pump water in a prior case study. The calculated values were compared with the metered data. The comparison analysis revealed a 41 percent error. (deMonsabert & Bakhshi, A GIS Methodology for Estimating the Carbon Footprint in Municipal Water and Wastewater in Fairfax County, September 2009) Appendix D provides pump energy calculations for a lift station located in Lower Potomac, Fairfax County.

The embodied energy calculations for this research were limited to the energy requirements for treatment and distribution of water. For example, the study did not consider the energy consumption as the result of initial plant infrastructure construction and continuous expansion. The energy consumed as a normal part of plant operations other than electricity, such as natural gas used to heat facilities, or diesel fuel used in trucks for hauling sludge are outside of the scope of this investigation. The embodied energy for the following elements was not accounted for in the energy calculations:

- Plant expansion and construction
- Chemical production and transport to the plant
- Commuting or other motor vehicle operation
- Non-electric process operations
- Other end-uses after the water service connection, e.g. hot water heating
- Power transmission loss

This research focused on the electrical intensive elements, and treated each sub-system as a black box. Electrical utility data for both water and wastewater treatment were collected and incorporated in the model in terms of MWh/Mgal treated. The GIS approach displayed the estimated energy consumption per unit of water usage for each service connection (MWh/Mgal). Specific elements of the GIS based model are described below.

Defined Boundary

The estimation of the carbon footprint associated with the embodied energy is comprised of the energy from the four sub-systems mentioned previously. Each of the subsystems is broken geographically into polygons and point features that represent areas served by the same water pump station, wastewater treatment plant, water treatment plant, and lift station. For example, the sewer collection subsystem is divided into sewershed areas. The water collected from a specific sewershed is assumed to exert the same footprint on a per unit basis throughout the sewershed. In defining a boundary for the CO_2 equivalent estimation, the polygon area that represents the intersection of all four sub-systems is modeled. The energy consumption and CO_2 factor represent the sum of the factors for each subsystem. The energy consumed and the associated carbon footprint factors are defined per gallon of water as tons of CO_2 or MWh and identified as attributes of the polygon feature class representing a geographical area. The carbon footprint for an individual facility may be determined by performing an algorithm embedded in the GIS model based on the customer demand as determined from the utility bill.

A parcel defined by census identifies the cluster of customers, type of customer, and customer water demand magnitude. The parcel polygon is within a defined boundary for water distribution, a sewershed boundary polygon, a water treatment and wastewater treatment coverage area. Having calculated the embodied energy for each segment of the water cycle in terms of MWh/Mgal, the total embodied energy of delivered water to the customer may be determined by applying a set of derived equations, algorithm and by performing spatial analysis in GIS.

Water Treatment and Wastewater Treatment Data

The GIS layer for the water treatment plant service areas is coupled with the GIS layer for the wastewater treatment plant area. For the research, data for each segment of the water cycle was used and incorporated into the GIS model.

Water Distribution and Sewage Collection

The energy consumption associated with a network of pump stations for delivery of treated water to a specific utility service zone may be obtained using the electrical meter reading data for the pump stations and the GIS layer showing the distribution network. Wastewater collection data are organized by sewershed. The data differ from the water distribution data in that wastewater is designed to maximize gravity flow wherever possible. Lift stations are used to elevate the wastewater to a level that enables gravity flow. The water distribution GIS dataset from the water utility company must be handled with sensitivity due to drinking water supply infrastructure security concerns after September 11, 2001.

GIS Dataset Availability

More and more water and wastewater utilities are taking advantage of GIS mapping systems to help manage the operation and maintenance and track inventory of their infrastructure. The guidelines and algorithms provided in this model will be applicable to any service area for which potable water distribution and sewage collection information is available in GIS format provided that information on the critical parameters, e.g. Pipe network, pressure zones, pumps location, extend of service for water and wastewater have been collected and tabulated as layers features and attributes. In addition, the data needed for the energy calculations may exist in spreadsheets; however, many of the attributes needed may not be readily available for incorporation in the GIS without manipulation by script or macro. The intent was to develop simple and easy to use carbon footprint estimation model without reliance on the elaborate scripts. Future improvement to the developed model may integrate an Access database of energy consumption and flow data with the GIS model.

Data Collection

Sources of data vary for each study, so close collaboration with the municipal utilities is imperative. Lack of digital data could be a major impediment to conduct spatial analysis of the water- energy carbon footprint model. For this study, data was collected from the Fairfax Water, the Loudoun Water and the District of Columbia Water and Sanitary Authority (DC WASA). Appendix B includes a template for data request from municipalities. Development of the model requires the collection of data from the water segment, the wastewater segment and the electrical power utilities. The minimum amount of information required in a GIS dataset is presented below:

- Water distribution infrastructure such as piping network, pipe sizes
- Water pump station location, and area of service
- Wastewater collection infrastructure, lift stations, sewer pipe distribution
- Customer parcel location and flow demand

In addition, the appropriate municipality must provide:

- Quantity of flow and energy consumption for treatment of raw water
- Quantity of wastewater flow and energy consumption for treatment
- Quantity of collected sewer and energy consumption for pumped sewer
- Quantity of potable water and energy consumption for pump station
- Identification of electric power for each subsystem
- Power company emission coefficient (Tons of Co_2/ MWh)

Most of the data handling can be performed by the operation staff of the municipalities. It is important to note that carbon footprint estimation may be broadened by the following recommendations:

- Improve data collection by requesting periodical updates
- Increase granularity of geographic disaggregation
- Expand attributes of layer features
- Optimize data input applying a database

Database Structure

In the creation of a database for this study, the following steps were followed:

1. Created a project database and designed attributes and shapefiles
2. Prepared data for analysis and performed required calculations
3. Analyzed data and presented the results in geospatial format

Table 7 lists some of the layers that were assembled for the project database:

Table 7: GIS Dataset Required for a Typical Project

Layer	Format
Water Pump station	Shapefiles
Wastewater Pump station	Shapefiles
Water and Wastewater treatment location	Shapefiles
Customer Water consumption	Shapefiles
Customer parcel	Shapefiles
Water Pipe Distribution	Geodatabase
Wastewater pipe network	Geodatabase
Sewershed zones	Geodatabase

The GIS based model determines embodied energy information for a parcel, or a customer. The structure utilizes data such as census, topography, customer water demand, wastewater collection network, water distribution infrastructure, etc. The graphical output can be shown in maps and can be overlaid with other thematic maps for further environmental impact analysis. Queries and searches may be performed using various criteria. The visualization tools in the GIS allow finding patterns and relationships as relate to the embodied energy of particular areas. What-if scenarios may also be generated to support decision making effort.

The following coordinate system is related to the dataset used for this research:

Geographic Coordinate System: GCS_North_American_1983_HARN
Datum: D_North_American_1983_HARN
Projected Coordinate system:
NAD_1983_HARN_StatePlane_Virginia_North_FIPS_4501_Feet
Projection: Lambert_Conformal_Conic

Source of Electricity

Greenhouse gas (GHG) production is directly related to the power generation fuel mix for a specific region. Information on the nature of electricity from the electric generators serving the treatment plants was obtained. Percentages of the non renewal energy and fossil fuel use can be used in the absence of the power generator emission coefficient to estimate the global warming potential contribution of the delivered electricity (Tons CO_2 equivalent per MWh). This model bases the GHG calculation on the power generator emission coefficient for the electric power utilities in the study. The coefficient may also be calculated or an average value obtained from government reference manuals. (DOE, 2002)

CHAPTER 5- EMBODIED ENERGY ESTIMATION MODEL

Overall Approach

This research developed a carbon footprint estimation model (embodied energy metric) that would improve the ability of water and wastewater utilities, municipalities, and land developers to predict the environmental burdens created by energy consumption for water and wastewater treatment and distribution.

A Geographical Information System framework model (ArcGIS for Desktop Application, Ver. 9.2) was devised and used for presenting the energy consumption estimates associated with the collection, treatment and distribution of drinking water and subsequent wastewater collection and treatment (embodied energy). The carbon dioxide emission estimation was based on the actual reported energy consumptions for energy intensive elements in an integrated water and wastewater system. The GIS dataset for a region with municipal water and wastewater infrastructure and distribution was obtained for integration with electrical power data. The GIS based approach focused on the energy intensive elements, and treated each sub-system as a black box. Electrical utility data for both water and wastewater treatment were incorporated. The developed GIS model revealed the key environmental indicators attributed to water cycle for a specific geographical area by incorporation of the collection and distribution energy (e.g. actual reported data from the pumping stations) and displayed the estimated annual energy consumption per unit of water usage (MWh/Mgal).

The following flow chart diagram (Figure 5) shows the multiple steps that were followed in the development of the model for estimation of energy-water metrics of the water cycle under study. Figure 6 shows the GIS flowchart of the model work flows.

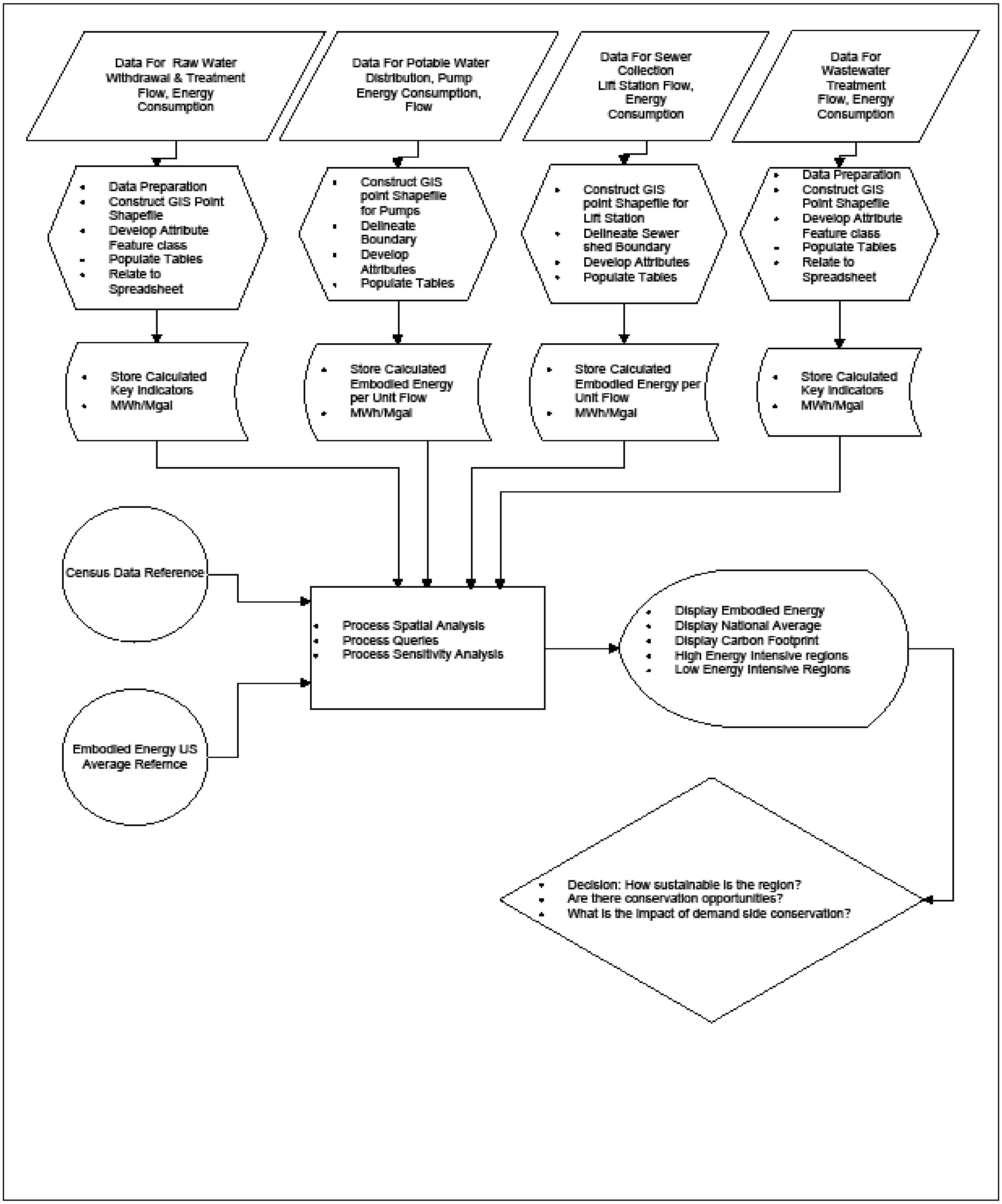

Figure 5: Model Process Schematic

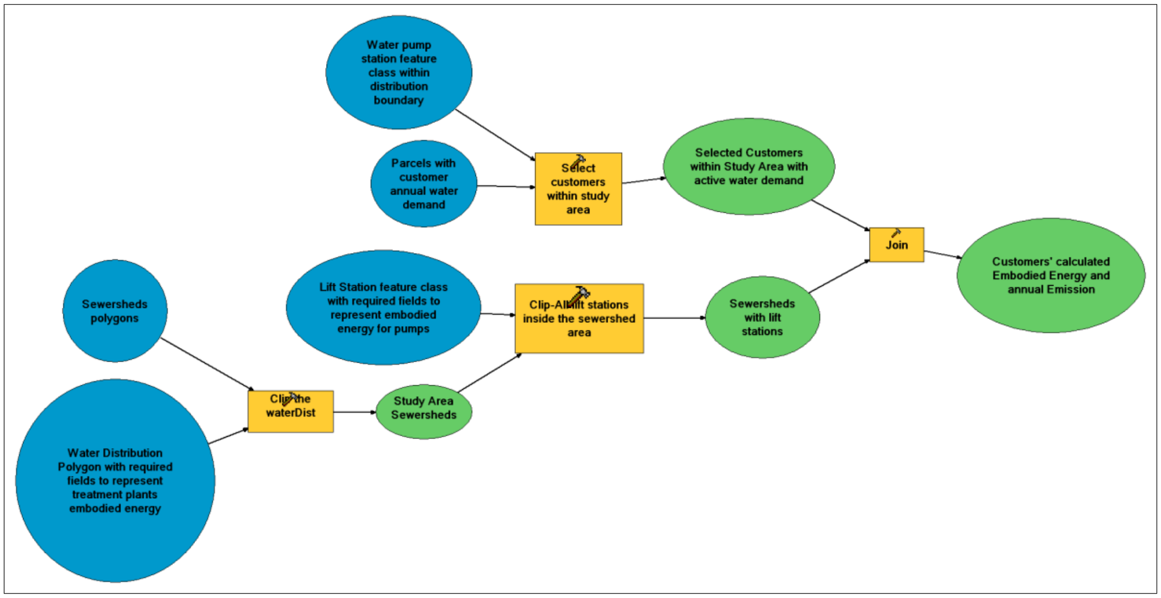

Figure 6: GIS Model Work Flow Processes

Emission Coefficient

Energy related activities produce emissions of some gases whose radiating effect warms the atmosphere in a process known as the greenhouse gas (GHG) effect. Gases such as Carbon Dioxide (CO_2), Methane (CH_4) and Nitrous Oxide (N_2O) are produced from generation of electricity from coal, fossil fuel or natural gas combustion. The GHG emission from combustion and human manufacture of hydrochloroflourocarbons (HCFC) chemicals can promote global warming. The greenhouse effect occurs as GHG gases absorb the long wave radiated solar energy in the atmosphere and warm the planet. The Earth absorbs short wave solar energy radiation and radiates back into atmosphere the long wave. CO_2 has been recognized as the main contributor of the GHG effect. The degree of warming attributed to other GHGs is normalized to an equivalent amount of

CO_2 expressed in metric tons ($MTCO_2E$). Greenhouse gases vary in the amount they warm the atmosphere and the time they remain in the atmosphere. These factors (radiation magnitude and atmospheric lifetime) determine GHG global warming potential (GWP). GWP allows for comparison among all GHGs in terms of $MTCO_2E$. To reduce the risk of climate change due to global warming, the world has attempted to reduce the atmospheric concentration of GHGs. This research uses the power generating utility's emission coefficient factor to estimate the greenhouse gas effect and global warming potential attributed to the water and wastewater life cycle.

GHG emission can be estimated for any activity that uses fossil fuel. Municipalities purchase electricity from a power company for operation of treatment and distribution of water. GHG emission of purchased electricity can be estimated by referring to the power generation company emission coefficient in terms of $MTCO_2E$/MWh, or by calculating $MTCO_2E$ from the fuel mix and the percent of each generation source (coal, natural gas, fuel oil). A factor can be applied to include the transportation losses and production efficiencies of each method of electricity generation. The following formula may be applied for GHG emission calculation (DOE-EPA, 2000):

$$\text{GHG Emission} = \text{Source Unit Consumed (Tons of coal, or barrel of fuel oil)} \times \text{Emission Coefficient} \left(\frac{\text{MTCO2E}}{\text{Tons of coal}}, \frac{\text{MTCO2E}}{\text{Barrel of oil}}\right) \quad \text{(Eq. 7)}$$

GHG emissions from a power generating plant are CO_2, CH_4, and N_2O reported in terms of $MTCO_2E$. Carbon dioxide emissions from fossil fuel combustion can be calculated applying a method presented in the reference. (EPA, ANNEX 4 IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion, 2006c) The following methodology shows how the emission coefficient of CO_2 for coal combustion is determined by converting the consumed fossil fuel from coal to energy in terms of British Thermal Units (Btus), and using the carbon content coefficient of the fuel. Similarly, emission coefficient may be calculated for CH_4, and N_2O.

$$\mathrm{CO2} = 24.82\left(\frac{\mathrm{MBtu}}{\mathrm{TonsCoal}}\right) \times 56\ \left(\frac{\mathrm{Lbs}}{\mathrm{MBtu}}\right) \times 3.67\left(\frac{\mathrm{MTCO2E}}{\mathrm{MT-C}}\right) \times 1\ \left(\frac{\mathrm{MT-C}}{2{,}204.62\mathrm{Lbs}}\right) = 2.31\ \left(\frac{\mathrm{MTCO2E}}{\mathrm{TonCoal}}\right) \qquad \text{(Eq. 8)}$$

Where:

1 Short ton of Coal= 24.82 Million Btus (MBtus);
Bituminous Coal Carbon Content, C= 56 lbs/ MBtus
1 Ton of C= 2000 Lbs of C
1 Ton= 0.9072 Metric Tons (MTons)
1 Metric Tons of C= 3.67 MTCO2E (molecular weight of CO_2-to-atomic weight of C)

For this research, Potomac Electric Power Company (Pepco) provides electricity to the Blue Plains Wastewater Treatment Plant. The emission coefficient of 1,220 lbs of CO_2/MWH (0.55 Tons of CO_2/MWh) was used in the energy calculations based on the information reported by the power company. The Energy source fuel mix for the Potomac Electric Power Company during 2008 is also provided in Appendix A. (PEPCO, 2008)

Electricity to water treatment plant and pump stations is supplied by Dominion Virginia Power Company. (DominionPower, 2008) The emission coefficient of 0.49 tons of CO_2/MWh was used in estimation of emission calculations for year 2008. Figure 7, shows the metric tons of carbon dioxide per megawatt hour of electricity produced by the Dominion for last few years. The coefficient typically declines as the company acquires or builds non-greenhouse gas emitting power generation. The emissions reported for carbon dioxide being emitted from the stacks to the atmosphere is based on the combustion of carbon-based fuels.

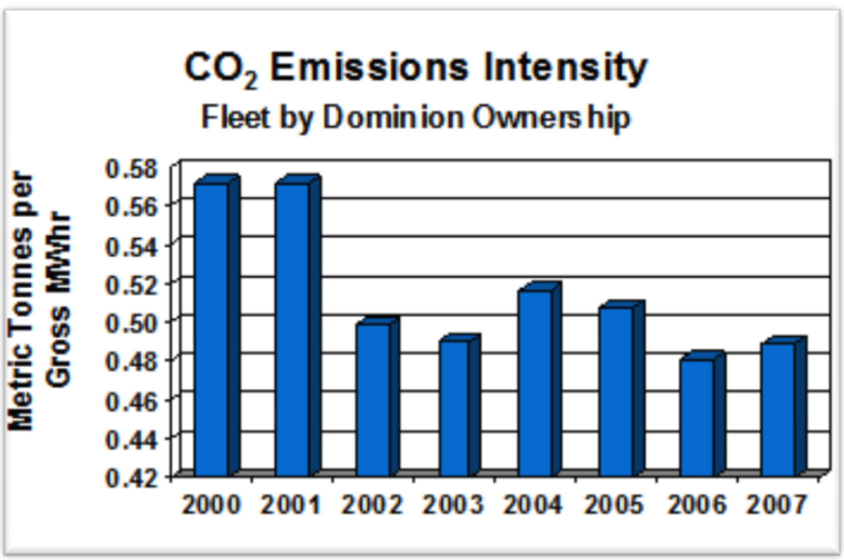

Figure 7: Dominion Power Company GHG Generation Intensity[9]

[9] Source: Dominion Virginia Electric Utility- Environmental Report

Study Area

The water, and wastewater infrastructure systems identified below were investigated and data was collected based on the availability and collaboration of those utility companies for testing of the GIS model:

Case Study- Dulles South Region and Brambelton Area in Loudoun County

Loudoun Water data was used to define preferred regions that include the GIS dataset for an entire water and wastewater infrastructure system. The Dulles South region and Brambelton area were selected on the basis of data availability for 2008. Three major municipal water and wastewater authorities were involved to undertake this case study. Fairfax County Water Authority (Fairfax Water), supplies water to Loudoun County, Virginia via James J. Corbalis, Jr. Water Treatment Plant. The energy consumption for the treatment of purchased water delivered to Loudoun Water was obtained and used in the carbon footprint estimation. The District of Columbia Water and Sewer Authority (DCWASA), Blue Plains Wastewater Treatment Plant, treats and manages all the sewage collected from Loudoun Water.

The Loudoun County Water Authority (Loudoun Water) is the party responsible for management and maintenance of the water distribution and wastewater collection system infrastructure in this coverage. The GIS dataset and energy consumption data for water distribution and sewer collection were obtained. The information provided for research purposes was secured under the water infrastructure protection regulations of the national water security mandate.

CHAPTER 6- CASE STUDY

The research included several coverage areas managed by different authorities and municipalities across District of Columbia, Fairfax County and Loudoun County. The following describes each phases of the research in detail.

Two areas south of the Dulles airport in Loudoun County were selected to apply the GIS model for the carbon footprint estimation of an entire water cycle. The model contained a GIS database structure that utilized pertinent Loudoun Water data for water treatment, wastewater treatment, water distribution, and sewer collection. Information can be viewed selectively with different layers switched on and off. The GIS graphical output of the embodied energy can be shown. Maps of low and high zones of embodied energy can be viewed across the region of the study. Information on the embodied energy of delivered water can be revealed on the customers within the region. Queries can be made using varying criteria; for example, an area of the lowest carbon footprint can be explored.

Water and Wastewater Treatment Boundary

The area of study included the southern region of Loudoun County. This region does not have a municipal water treatment plant within its county boundary. Finished water is purchased from the James Corbalis Water Treatment Plant operated by Fairfax Water. The purchased quantity of water is pumped by the RT50 Pump station and the Brambelton Pump Station and distributed to customers within Dulles South region and Brambelton zone. The wastewater flow is collected via multiple sewer lift stations and delivered to the Blue Plains Wastewater Treatment Plant by force and gravity mains. It is conveyed by the Upper Broad Run interceptor and Potomac interceptor. [10] Figures 8 and 9 show the study area and the water segment boundaries.

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[10] Fairfax County Government FY 2008 budget expenditure: www.fairfaxcounty.gov/dmb/adopted/FY2008/.../Water_Supply.PDF

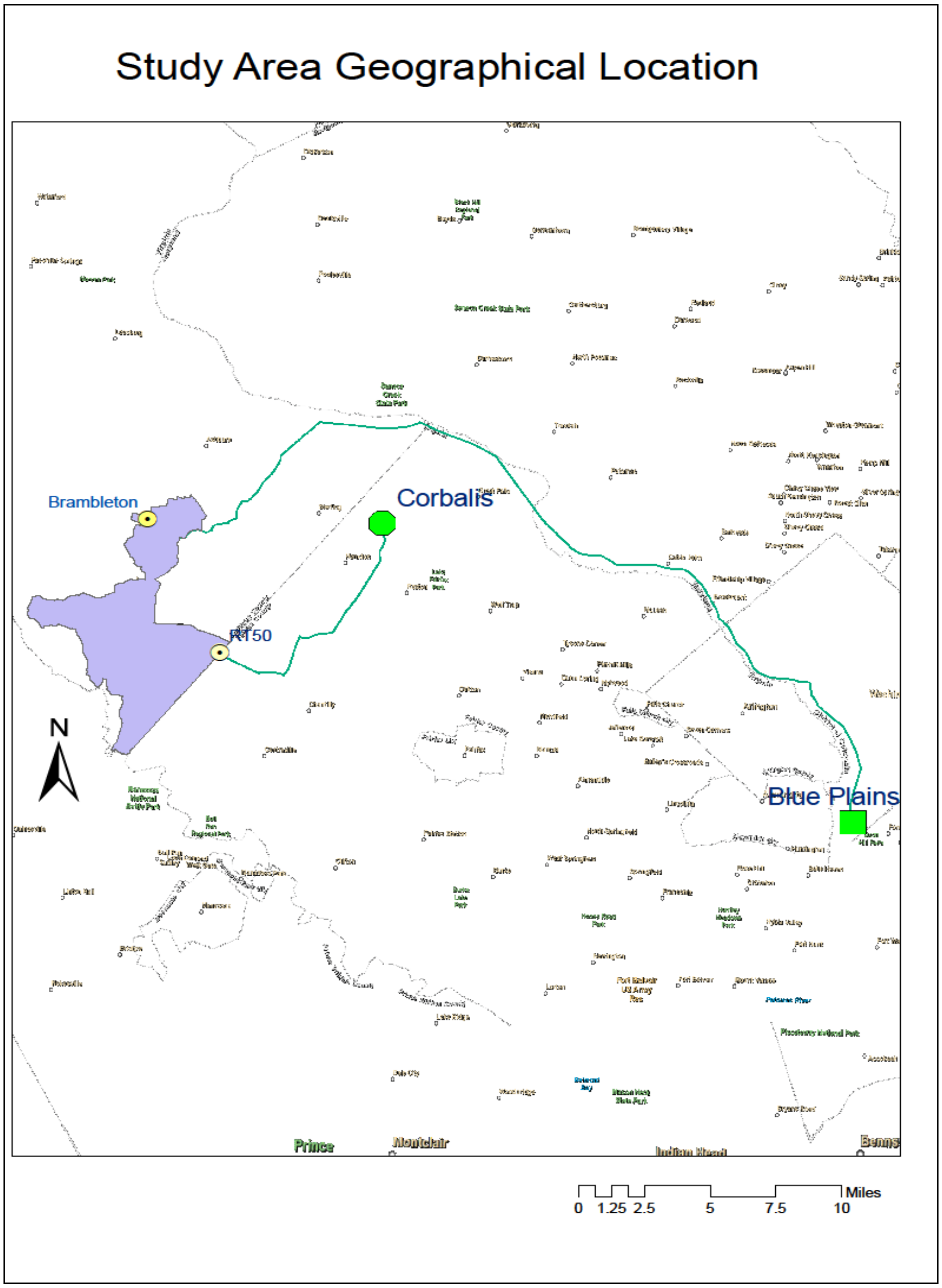


Figure 8: Loudoun Water Cycle Overall Geographical Location

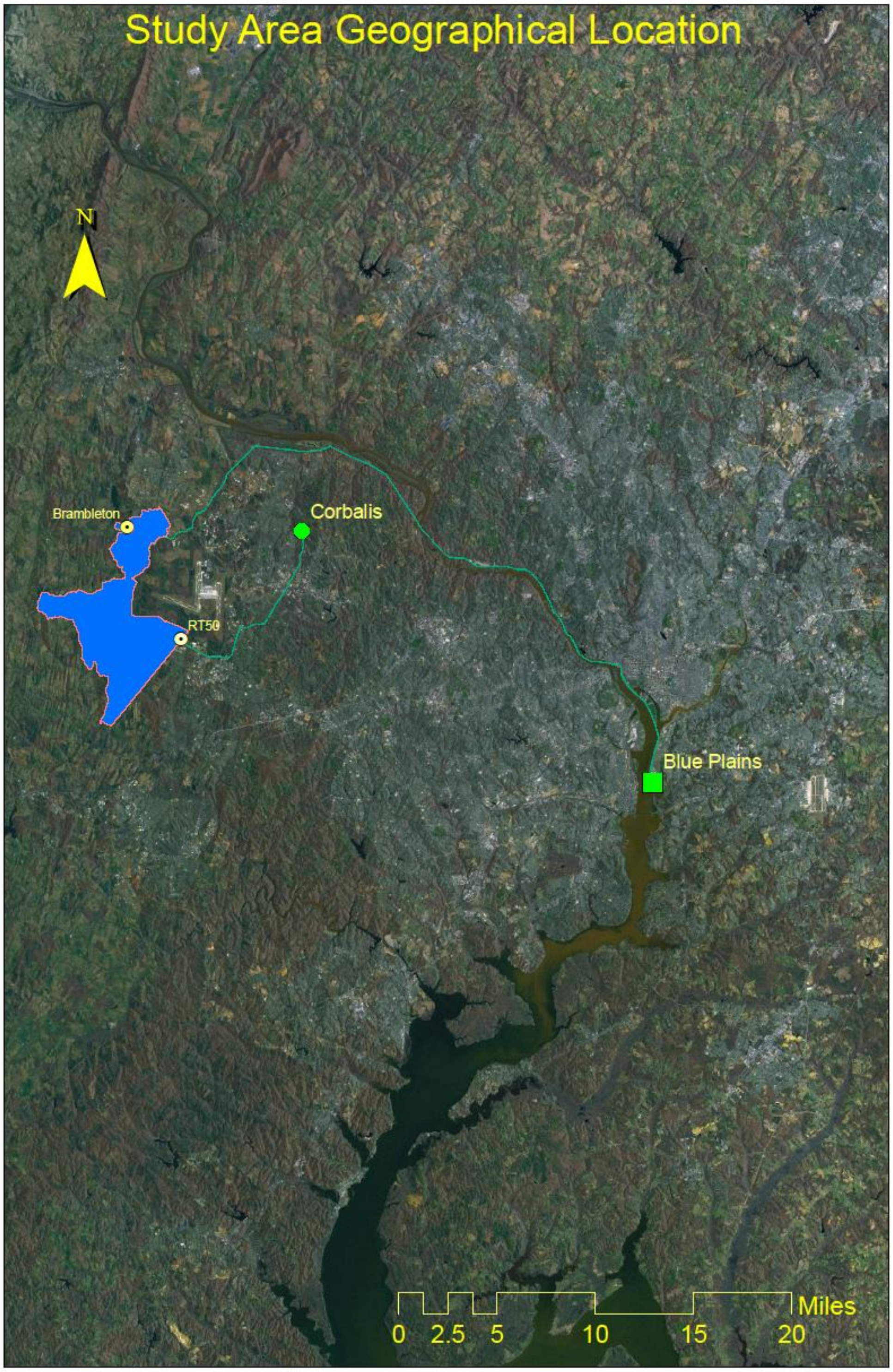


Figure 9: Loudoun Water Case Study

James J. Corbalis Jr. Water Treatment Plant

The Corbalis Water Treatment Plant (Fig. 10), located in Herndon Virginia, is owned and operated by Fairfax Water Authority. It provides potable water to nearly 1.5 million people in northern Virginia. The principal sources of water for Fairfax Water are the Occoquan River and the Potomac River (Potomac River basin). Fairfax Water extracts the water from the middle of the Potomac River for the Corbalis Plant water intake. The facility current capacity is 150 million gallons per day. The future planned expansion will increase the capacity to 225 million gallons per day. Loudoun Water purchases finished water from this treatment plant to supply the Dulles South region and Brambelton zone among other areas.[11] Treatment processes include coagulation, control of taste and odors, fluoridation, and disinfection. The plant sells water to Loudoun Water. Reportedly, 54,900 million gallons per year of potable water is delivered to all regions. Under Loudoun Water, RT50 Pump station delivers 1,606 million gallons of the total purchased drinking water to Dulles South Region.

[11] Fairfax Water Authority website: http://www.fcwa.org/


Figure 10: James J. Corbalis, Jr. Water Treatment Plant

Table 8 shows the embodied energy of treated raw water by the Corbalis Water Treatment Plant. It is 2.31MWh/Mgal on average for year 2008. This metric encompasses the energy of pumping raw water from the Potomac River to the plant. The total emission of carbon dioxide equivalent for the same period generated from operation of the plant is estimated at 35,091 Tons. Figures 11, 12, and 13 graphically show the magnitude of emission, intake water, and energy consumption for treatment.

Table 8: Embodied Energy and GHG Estimate - Corbalis

Month/Year	Water Treatment Flow (Mgal)	Energy Consumption Water Treatment (MWh)	Embodied Energy of Treated Water (MWh/Mgal)	Emission per unit of Treated Water (Tons of CO2/Mgal)	Emission Tons of CO_2
Jan-08	2,115.00	4,690.00	2.22	1.09	2,298.10
Feb	1,859.00	4,658.50	2.51	1.23	2,282.67
Mar	2,076.00	4,980.50	2.40	1.18	2,440.45
Apr	2,054.00	5,012.00	2.44	1.20	2,455.88
May	2,694.00	5,673.50	2.11	1.03	2,780.02
Jun	3,061.00	6,289.50	2.05	1.01	3,081.86
Jul	3,411.00	8,120.00	2.38	1.17	3,978.80
Aug	3,733.00	7,801.50	2.09	1.02	3,822.74
Sep	2,931.00	7,241.50	2.47	1.21	3,548.34
Oct	2,750.00	5,057.50	1.84	0.90	2,478.18
Nov	2,171.00	5,999.00	2.76	1.35	2,939.51
Dec	2,203.00	6,090.00	2.76	1.35	2,984.10
Total	31,058.00	71,613.50			35,090.62
Mean			2.31	1.13	

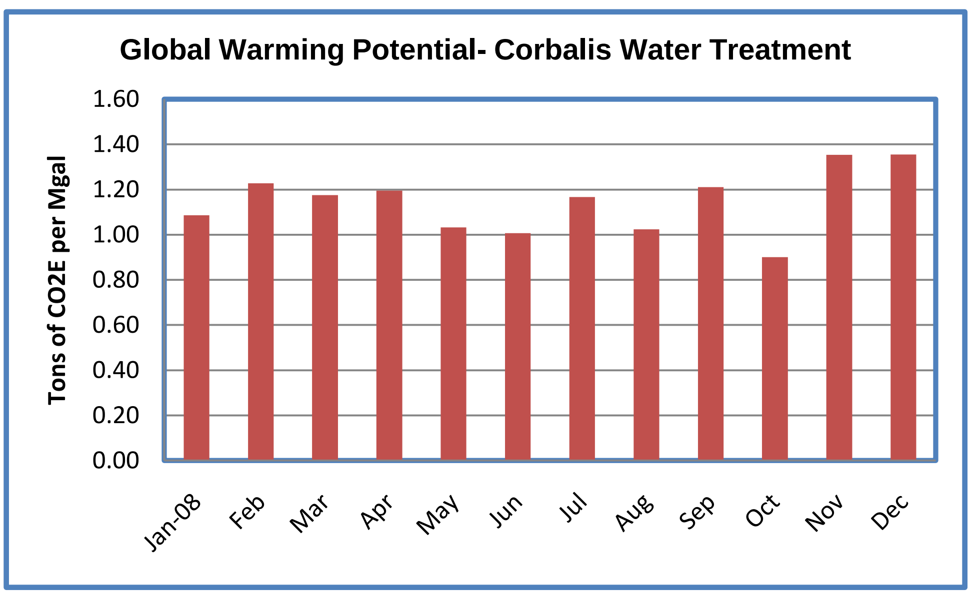


Figure 11: Corbalis Water Treatment Plant Emission Magnitude

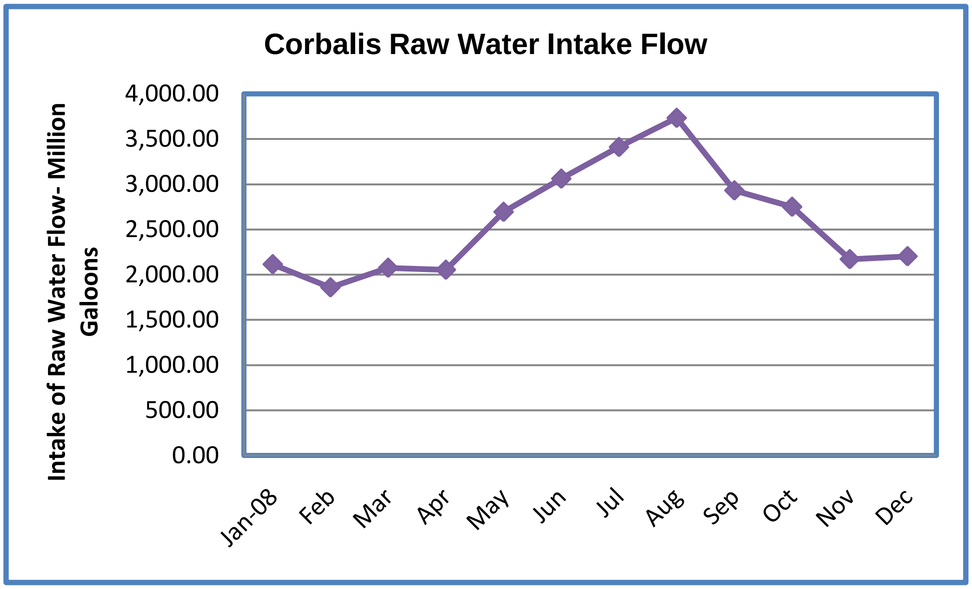


Figure 12: Corbalis Water Treatment Plant Flow Profile

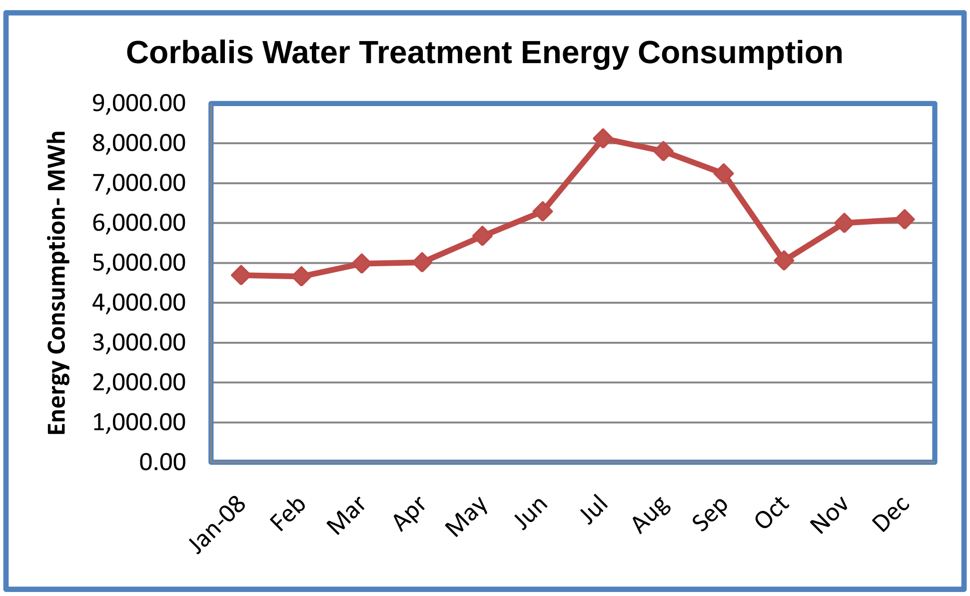


Figure 13: Corbalis Water Treatment Plant Energy Consumption

Blue Plains Wastewater Treatment Plant

Loudoun County, Virginia, delivers wastewater to the Blue Plains Advanced Wastewater Treatment Plant (Fig. 14) located in the city of Washington, District of Columbia. Wastewater travels approximately 204,100 feet from the northern most tip of the study boundary to the treatment plant. Blue Plains is an advanced wastewater treatment facility with an annual average capacity of 370 million gallons per day (MGPD). Blue Plains' twelve month average flow in 2008-2009 is attributed to DC (148 MGPD), WSSC (169.6 MGPD), Fairfax County (31.0 MGPD), Loudoun County (13.8 MGPD), Town of Vienna (1.5 MGPD), Dulles (1.5 MGPD), Navy (0.1 MGPD), and others (4.5 MGPD). Only about four percent of the total flow is allocated to Loudoun Water. The Dulles South region and the Brambelton flow are directed to the Blue Plains plant. The treatment processes at Blue Plains consists of preliminary and primary treatment, secondary treatment, nitrification/denitrification, effluent filtration, chlorination/dechlorination and post aeration. The solids treatment processes at the Blue Plains use thickening and dewatering processes for primary sludge, secondary waste activated sludge, and nitrification/denitrification waste activated sludge. These processes include screen and degritting processes, gravity thickeners, dissolved air flotation thickeners, sludge blending centrifuge dewatering.[12] Table 9 provides the indirect emission and the embodied energy estimation of the Blue Plains Wastewater Treatment Plant. Figures 15,

[12] DC Sewer and Water Authority Website: http://www.dcwasa.com/

16 and 17 show graphically the magnitude of emission, and energy consumption for wastewater treatment.

Table 9: Embodied Energy- Blue Plains Wastewater Treatment Plant

Month/Year	Wastewater Flow (Mgal)	Energy Consumption treatment (MWh)	Embodied Energy of Treated Wastewater (MWh/Mgal)	Emission per unit of Treated Wastewater (Tons of CO_2/Mgal)
Jan-08	8,399.34	24,599	2.93	1.61
Feb	8,573.81	21,762	2.54	1.40
Mar	17,608.00	23,894	1.36	0.75
Apr	9,564.99	21,431	2.24	1.23
May	11,387.79	20,420	1.79	0.99
Jun	9,527.74	21,266	2.23	1.23
Jul	9,107.80	22,847	2.51	1.38
Aug	8,234.76	20,311	2.47	1.36
Sep	8,854.81	22,817	2.58	1.42
Oct	8,288.19	20,319	2.45	1.35
Nov	8,064.63	20,441	2.53	1.39
Dec	8,884.51	24,443	2.75	1.51
Total	116,496.37	264,550		
Mean			2.27	1.25

Figure 14: The Blue Plains Wastewater Treatment Plant

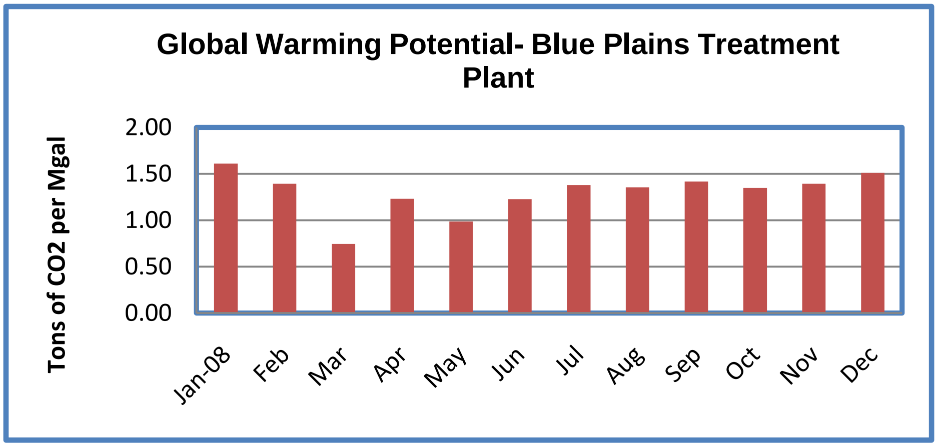


Figure15: Blue Plains Carbon Emission

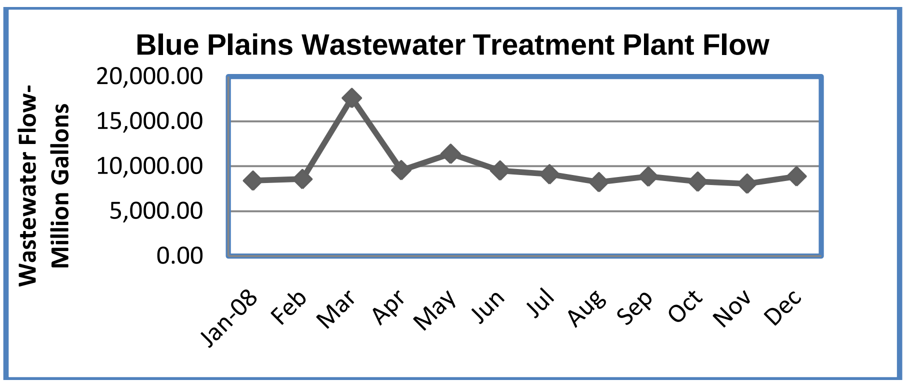


Figure 16: Blue Plains Treatment Plant Flow

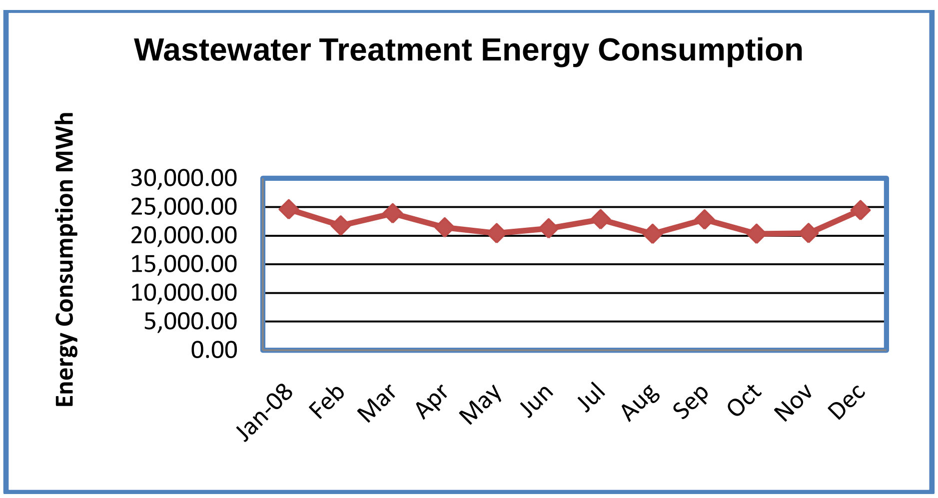


Figure 17: Blue Plains Treatment Plant Energy Consumption

Sewer Collection Boundary

The sewer from the region is collected by both forced and gravity mains. The study area contains several sewershed areas. A sewershed area may contain a lift station facility which services the customers within the same boundary. Customers may be identified by their addresses or land parcels. The portion of the wastewater flow that is pumped to the gravity main is of concern to this study. The total sewer flow and energy consumption for each lift station were obtained and incorporated into energy calculations for each sewershed. The sewersheds serving the study area is shown in Figure 18. The Brambelton area did not have any lift stations; sewage is collected by gravity.

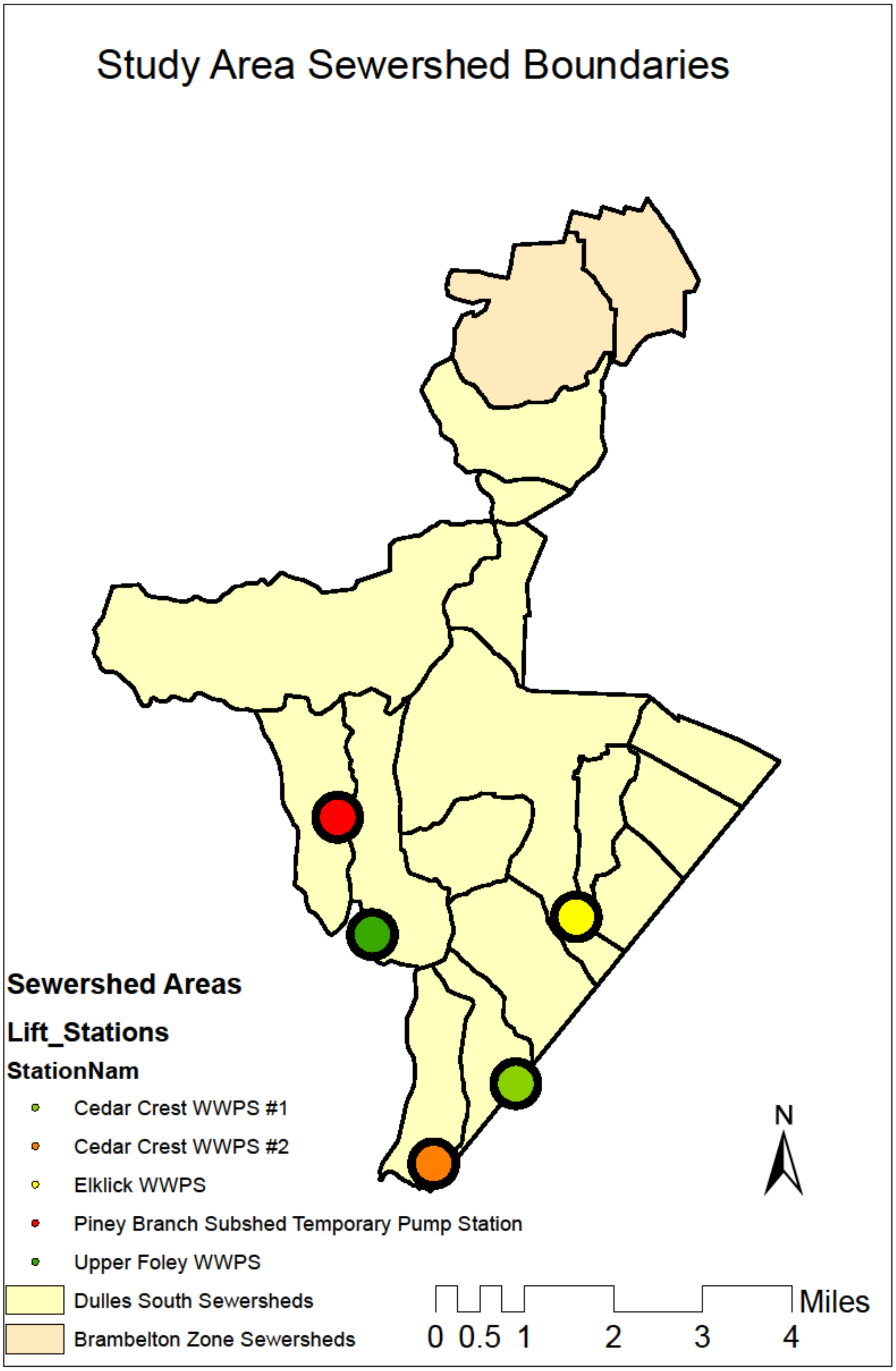


Figure 18: Wastewater Collection Boundary

Potable Water Distribution Boundary

The water distribution boundary is based on the extent of piping within the project boundary and sewershed areas of the study coverage. It is further disaggregated based on the number of water pump stations. Under this study, drinking water is purchased (1,606 Mgal per year) from the Corbalis Water Treatment Plant of Fairfax Water. Potable water for the Dulles South Region and the Brambelton area is conveyed via 59,200 feet of piping to the RT50 Pump station and the Brambelton Pump House operated by Loudoun Water. The energy consumption for conveyance is included as part of total energy reported for the water treatment GIS layer. The pump station configuration shown in Appendix E was taken from the Loudoun Water Supervisory Control and Data Acquisition (SCADA). Water conveyance to this pump station is done by a set of pumps owned and operated by Fairfax Water. Figure 22 shows the water distribution boundary and pipe network.

In order to gain more insight in the magnitude of the variables affecting the embodied energy for a water cycle, a zone in the Brambelton water distribution area within the Loudoun Water was selected for analysis and comparison. The customers' embodied energy and annual emission were determined using the model and the embodied energy calculation algorithm. This area is located in a different pressure zone (538 feet) for water distribution than Dulles South (510 feet), and is served by one pump station (Brambelton Pump House). Figures 19, 20, and 21 shows the water flow, energy consumption, and GHG impact of RT-50 pump house.

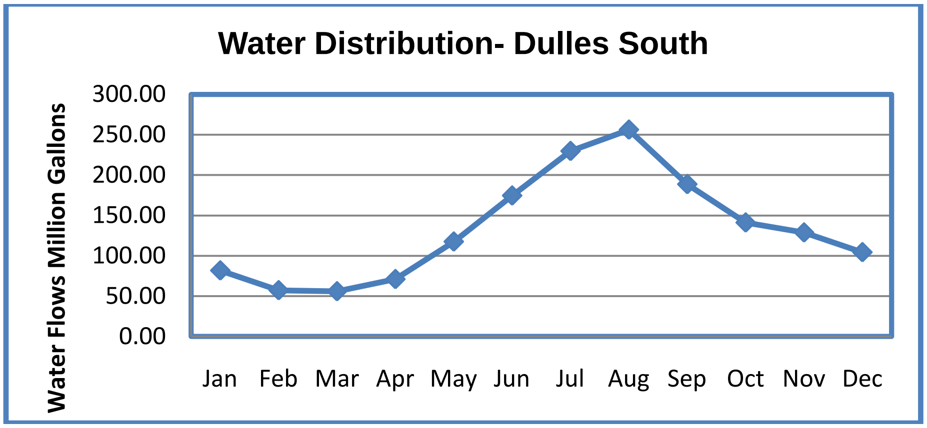


Figure 19: Dulles South Water Distribution Flow

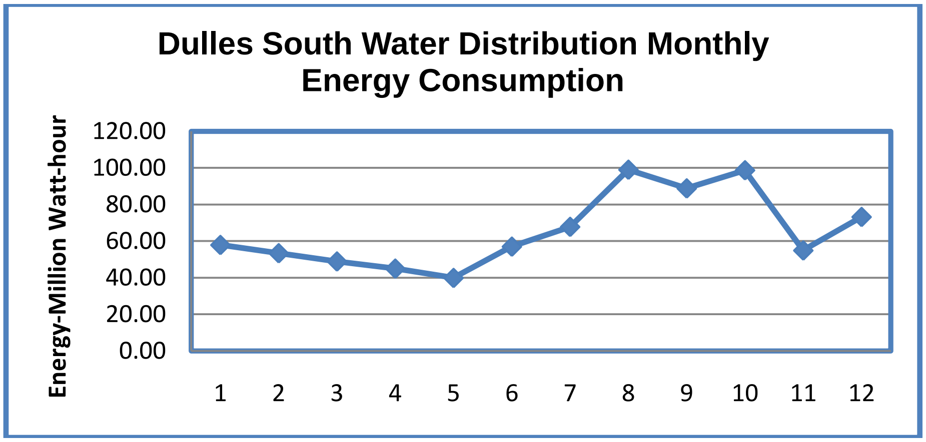


Figure 20: Dulles South Region Water Distribution Energy Consumption

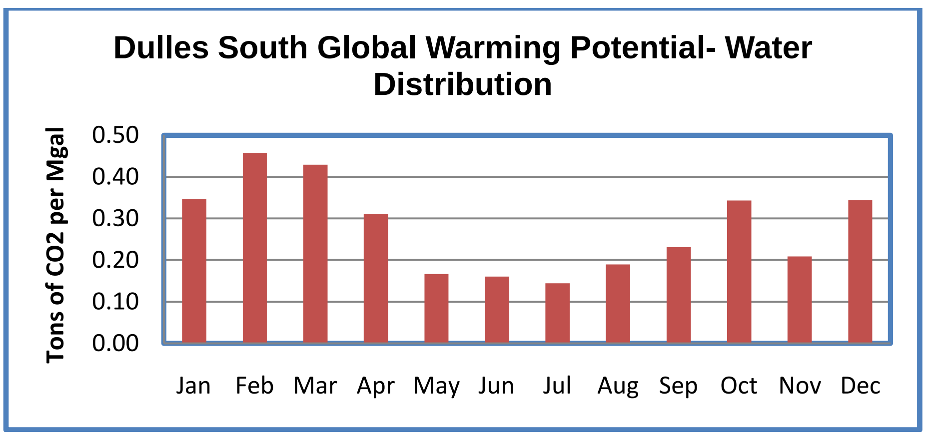


Figure 21: Dulles South Region Carbon Emission-Water Distribution

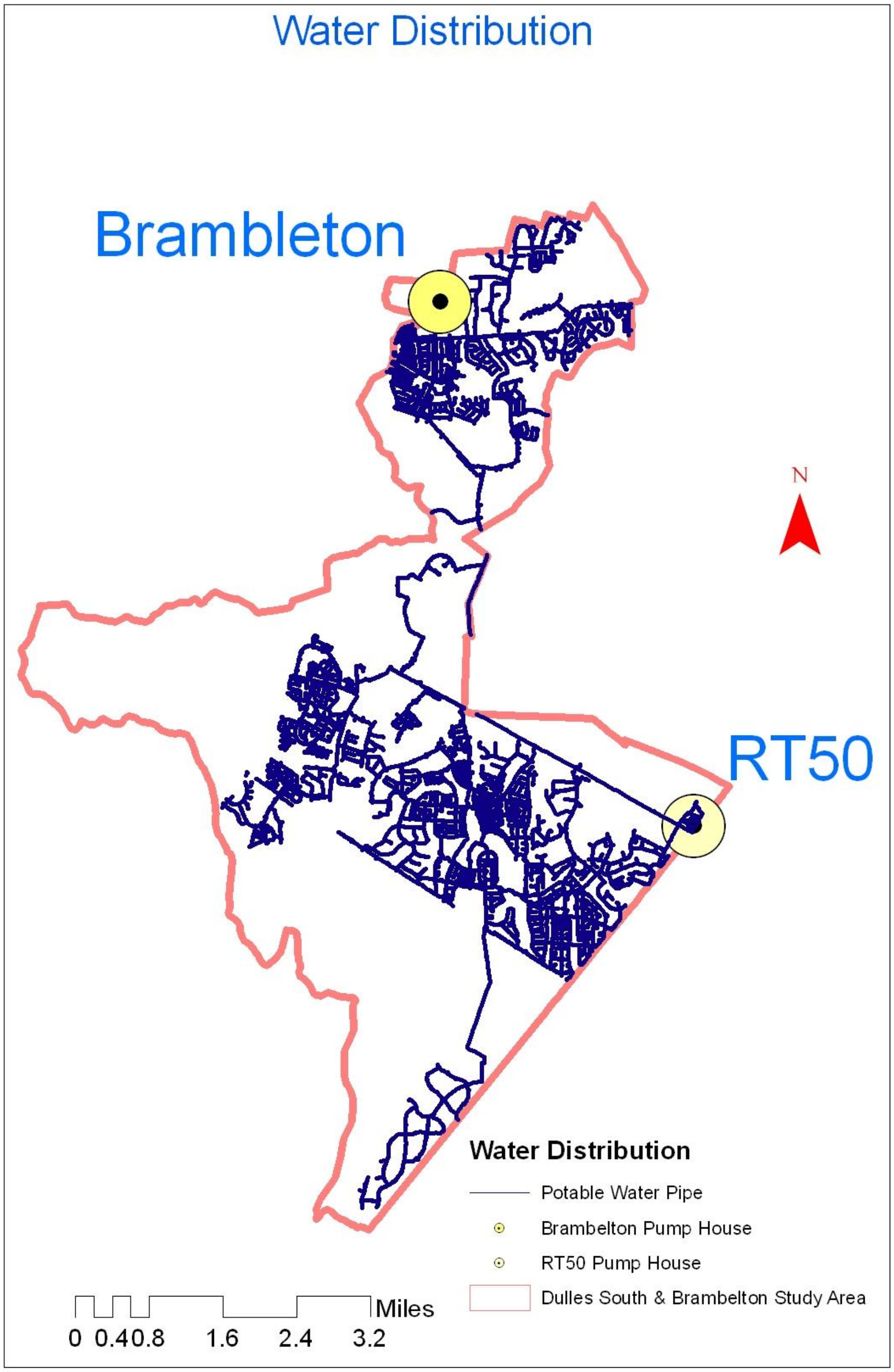


Figure 22: Water Distribution

Data Use Agreement

The geodatabase and consumption data for potable water pumping and wastewater collection were obtained from Loudoun Water. A "Data Use Agreement" was signed between GMU, Director of Sponsored Programs, Student Advisor, Student Research Faculty, and Loudoun Water to provide an assurance for the protection of sensitive water infrastructure during this research. A copy of the agreement is provided in Appendix C. The following describes the steps in developing the carbon estimation model.

Carbon Footprint Estimation Algorithms

The carbon footprint calculation related to the water distribution, wastewater collection, water treatment and wastewater treatment for the covered study area was performed utilizing the actual flow and energy consumption data. The calculations take into consideration the power company emission coefficient. There are two major power utility companies, namely, the Dominion Virginia Power and Pepco that generate power and supply electricity to northern Virginia (Loudoun Water/Corbalis water treatment plant) and Washington, DC (Blue Plains wastewater treatment plant). In addition, Northern Virginia Electric Cooperative (NOVEC) locally transmits power purchased from PJM in 2008. The PJM Interconnection is a regional transmission organization (RTO) that coordinates the movement of wholesale electricity in several states including the District of Columbia. It manages the high-voltage electric grid. Dominion Virginia is a member electricity generator that supplies power to the grid system for the "South

Market Region" under PJM management. The power for the Elklick lift station is supplied by NOVEC.

Table 10 shows the embodied energy for water treatment and distribution sectors is 2.80 MWh/Mgal (30% of total), and for wastewater collection and treatment sectors is 6.37 MWh/Mgal (70% of total).

Table 10: Embodied Energy Estimate -Dulles South Water Cycle

Name	Flow (Mgal/yr)	Energy Used (MWh/yr)	Embodied Energy (MWh/Mgal)	Power Generation Emission Coefficient- Metric Tons of CO2/MWh	Emission Intensity- GHG per Unit of Flow (Tons of CO2/Mgal)
Wastewater Collection- Loudoun Water (Dominion Power)					
Cedar Crest-1	5.85	33.60	5.74	0.49	2.81
Cedar Crest-2	5.21	29.94	5.74	0.49	2.81
Elklick	441.60	518.78	1.17	0.49	0.58
Upper Foley	105.82	396.86	3.75	0.49	1.84
Mean Value			4.10		2.01
Drinking Water Distribution- Loudoun Water (Dominion Power)					
RT-50	1,605.93	784.50	0.49	0.49	0.24
Water Treatment Plant- Fairfax Water (Dominion Power)					
Corbalis Plant	31,058.00	71,613.50	2.31	0.49	1.13
Wastewater Treatment Plant- DC WASA (Pepco)					
Blue Plains Plant	116,496.37	264,550.31	2.27	0.55	1.25
Total			9.17		4.63

For a typical customer, the overall embodied energy is determined by summing the aggregated energy for each segment of the water cycle as tabulated in Appendix F. A customer is associated with a parcel, and its water cycle segments. For example, the embodied energy calculations for a Dulles South customer considers the water flow that is treated by the Corbalis water treatment plant, and the Blue Plains wastewater treatment plant, distributed by the RT50 pump station, and collected by the Elklick lift station. The customer sewage flow is determined based on a selected ratio. For this research it is assumed that 80% of the customer water use is returned as sewage. This accounts for the irrigation, car wash, gardening, and human consumption. As an example, one selected customer's embodied energy is 5.55 Watt-hr/gallon; the emission intensity is 1.13 tons of CO_2/Mgal; and the annual environmental burden is 17.93 tons of CO_2 for the Dulles South Region water and wastewater life cycle.

The following equations were developed for use in the GIS model to determine the customer emission and the embodied energy attributed to his or her water consumption.

$$\mathrm{CUST_{WF}} = \mathrm{AGPD}\left(\frac{\mathrm{Gal}}{\mathrm{Day}}\right) \times \left(\frac{\mathrm{336\ Days}}{\mathrm{Yr}}\right) \div 1{,}000{,}000\,\frac{\mathrm{Gal}}{\mathrm{Mil{-}Gal}} \quad \text{(Eq. 9)}$$

$$\mathrm{CUST_{WWF}} = \mathrm{Fraction} \times \mathrm{CUST_{WF}} \quad \text{(Eq. 10)}$$

$$\mathrm{CUST_{WTPE}} = \mathrm{CUST_{WF}} \times \mathrm{WTP_{EMB}} \quad \text{(Eq. 11)}$$

$$\mathrm{CUST_{WPE}} = \mathrm{CUST_{WF}} \times \mathrm{WpumpEMB} \quad \text{(Eq. 12)}$$

$$\mathrm{CUST_{WWTPE}} = \mathrm{CUST_{WWF}} \times \mathrm{WWTP_{EMB}} \quad \text{(Eq. 13)}$$

$$\mathrm{CUST_{WWPE}} = \mathrm{CUST_{WWF}} \times \mathrm{WWpumpEMB} \quad \text{(Eq. 14)}$$

$$\mathrm{CUST_{Em}} = (\mathrm{CUST_{WTPE}} \times \mathrm{WTP_{EC}}) + (\mathrm{CUST_{WPE}} \times \mathrm{WpumpEC}) + (\mathrm{CUST_{WWTPE}} \times \mathrm{WWTP_{EC}}) + (\mathrm{CUST_{WWPE}} \times \mathrm{WWpumpEC}) \quad \text{(Eq. 15)}$$

$$CUST_{EI} = WTP_{EI} + WPUMP_{EI} + WWPUMP_{EI} + WWTP_{EI} \quad \text{(Eq. 16)}$$

$$CUST_{TOTE} = CUST_{WTPE} + CUST_{WPE} + CUST_{WWPE} + CUST_{WWTPE} \quad \text{(Eq. 17)}$$

$$CUST_{EMB} = CUST_{TOTE} \div CUST_{WF} \quad \text{(Eq. 18)}$$

Where:

AGPD= Average Gallons Per Day

$CUST_{WF}$ = Customer Water Demand, (Mgal/Yr)

Fraction= Ratio of Customer Wastewater Collected to Water Demand, (80%)

$CUST_{WWF}$= Customer Wastewater Flow, (Mgal/Yr)

$CUST_{WTPE}$= Customer Energy Consumption Attributed to Water Treatment Plant, (MWh/Yr)

WTP_{EMB}= Water Treatment Plant Embodied Energy, (MWh/Mgal)

$CUST_{WPE}$= Customer Energy Consumption for Water Distribution, (MWh/Yr)

$WPump_{EMB}$= Embodied Energy for Water Distribution, (MWh/Mgal)

$CUST_{WWPE}$= Customer Energy Attributed to Lift Station, (MWh/Yr)

$WWPump_{EMB}$= Embodied Energy for Lift station, (MWh/Mgal)

$CUST_{WWTPE}$= Customer Energy Attributed to Wastewater Treatment Plant, (MWh/Yr)

$WWTP_{EMB}$= Embodied Energy Attributed to Wastewater Treatment Plant, (MWh/Mgal)

$CUST_{TOTE}$= Customer Total energy Attributed to Water Cycle, (MWh/Yr)

$CUST_{EMB}$= Customer Embodied Energy Attributed to Water Cycle, (MWh/Mgal)

WTP_{EC}= Emission Coefficient Attributed to Water Treatment Plant, (Tons/MWh)

$WPump_{EC}$ = Emission Coefficient Attributed to Water Distribution Pumps, (Tons/MWh)

$WWPump_{EC}$ = Emission Coefficient Attributed to Wastewater Collection Pumps, (Tons/MWh)

$WWTP_{EC}$ = Emission Coefficient Attributed to Wastewater Treatment Plant, (Tons/MWh)

$CUST_{Em}$ = Customer Annual Carbon Dioxide Emission, (Tons/Yr)

WTP_{EI} = Emission Intensity for Water Treatment Plant, (Tons/Mgal)

$WPump_{EI}$ = Emission Intensity for Water Pumps, (Tons/Mgal)

$WWPump_{EI}$ = Emission Intensity for Wastewater Pumps, (Tons/Mgal)

$WWTP_{EI}$ = Emission Intensity for Wastewater Treatment Plant, (Tons/Mgal)

$CUST_{EI}$ = Customer Emission Intensity for Water Cycle, (Tons/Mgal)

Tables 11 through 14 provides key parameters to estimate the customer impact of water use as it is associated with each segment of the water cycle.

Table 11: A Typical Commercial Customer GIS Output

Customer ID	Drinking Water Pump Station Name	Sewer shed Lift Station Name	Water Treatment Plant Name, Capacity (MGD)	Wastewater Treatment Plant Name, Capacity (MGD)	Parcel Sub Division Acre
4671	RT 50	Elklick	Corbalis, 150	Blue Plains, 370	1.265

Table 12: Embodied Energy Estimate- Water Treatment and Distribution

Customer ID	Customer Annual Water Demand Mgal	Water Treatment Plant Embodied Energy MWh/Mgal	Customer Energy Consumption Attributed to Water Treatment MWh	Water Distribution Embodied Energy MWh/Mgal	Customer Energy Consumption Attributed to Water Distribution MWh
4671	6.34	2.31	14.64	0.49	3.4

Table 13: Embodied Energy Estimate- Wastewater Treatment and Collection

Customer ID	Customer Estimated Sewer Flow Mgal	Wastewater Treatment Plant Embodied Energy MWh/Mgal	Customer Energy Consumption Attributed to Wastewater Treatment MWh	Sewer Collection Embodied Energy MWh/Mgal	Customer Energy Consumption Attributed to Sewer Collection MWh
4671	5.07	2.27	11.51	1.17	5.93

Table 14: A Customer Embodied Energy & GHG Estimation – Dulles South

Customer ID- 4671	Customer Annual Energy Use MWh	Emission Intensity Tons of CO_2/Mgal	Power Generation Emission Coefficient Metric Tons of CO_2/MWh	Customer Annual Emission, Tons of CO_2 per year	Annual Drinking Water Demand Mgal	Customer Embodied Energy MWh/Mgal
Water Treatment	14.64	1.13	0.49 [13]	7.17	6.34	5.55
Water Distribution & Conveyance	3.4	0.24	0.49	0.81		
Wastewater Treatment	11.51	1.25	0.55 [14]	6.33		
Sewer Collection	5.93	0.58	0.49	2.90		
Total	35.19	3.2		17.93		

[13] 2008 Annual CO_2 Emission Intensity for Electrical Generation- Dominion Power

[14] 2008 Annual Air Emission Report, PEPCO MD-6_09

Table 15 shows the result of the Brambelton water cycle emission and embodied energy calculations.

Table 15: Brambelton Zone Study

Name	Flow Mgal/yr	Energy Used MWh/yr	Embodied Energy MWh/Mgal	Emission Coefficient Tons of CO_2/MWh	Emission Intensity Tons of CO_2/Mgal
Wastewater Collection- Loudoun Water (Dominion Power)					
Gravity					
Drinking Water Distribution- Loudoun Water (Dominion Power)					
Brambelton Pump Station	1,395.58	396.86	0.28	0.49	0.14
Water Treatment Plant- Fairfax Water (Dominion Power)					
Corbalis Plant	31,058.00	71,613.50	2.31	0.49	1.13
Wastewater Treatment Plant- DCWASA (Pepco)					
Blue Plains Plant	116,496.37	264,550.31	2.27	0.55	1.25
Total			4.86		2.52

Figure 23 shows the three main pressure zones (510 ft, 538 ft, and 600 ft) that exist for the water delivery from the Corbalis Water Treatment Plant to the end users located inside the Loudoun Water boundary.

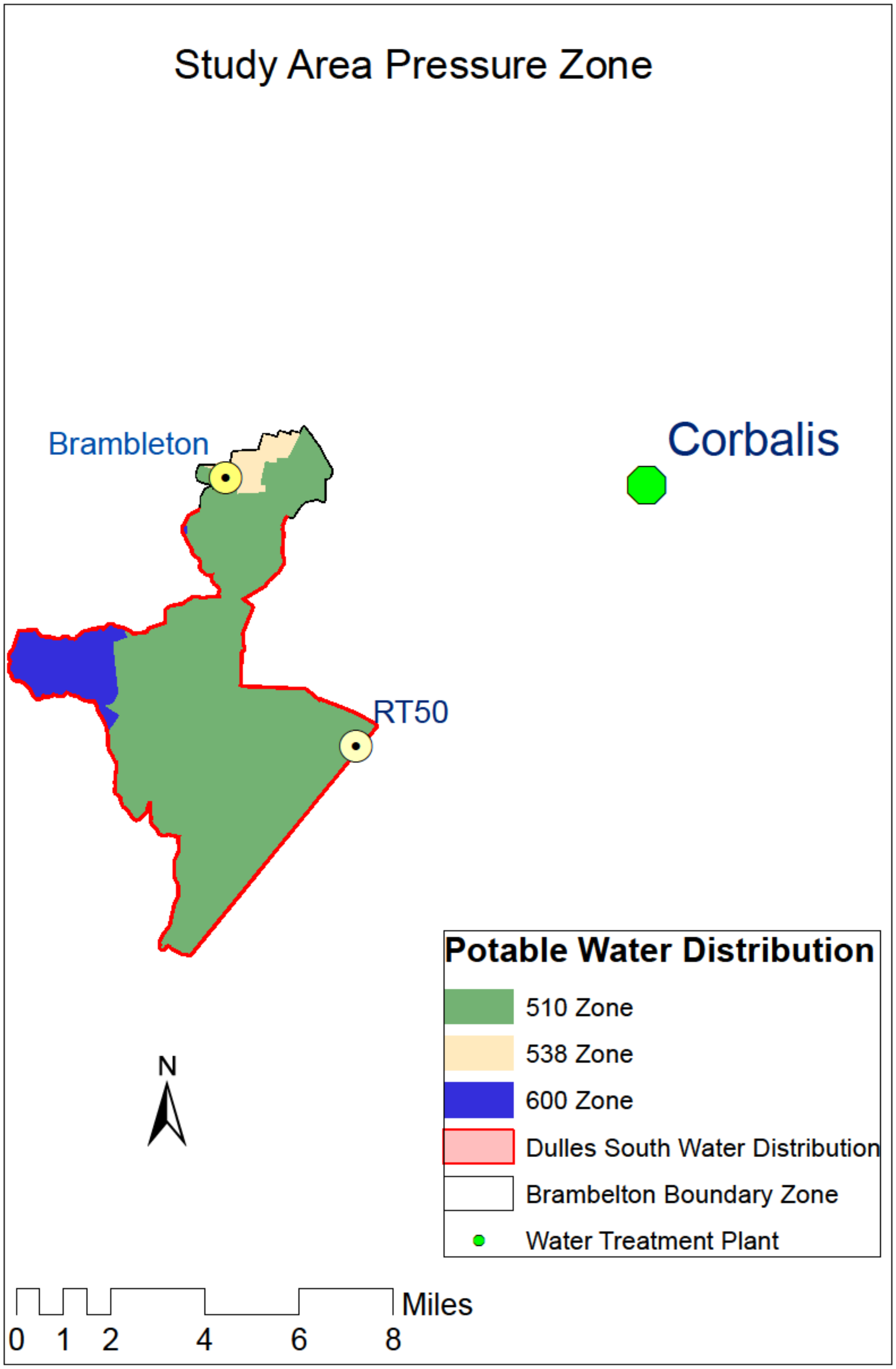


Figure 23: Loudoun Water Pressure Zones

CHAPTER 7 – RESULTS

The greenhouse gas emission model for the case study area was developed. The results of the embodied energy calculations are geospatially displayed in Figures 24, 25, and 26. The GIS output thematic maps for the end users' carbon footprint are presented in Figures 27, 28, and 29. The parcels without any water consumption demand were not accounted for in the model and are shown as white (blank) areas in the maps. The range of customers' embodied energy is from 4.4 to 7.2 Wh/gal. The range of customer annual carbon dioxide emission is from 0.008 to 17.93 tons of CO_2.

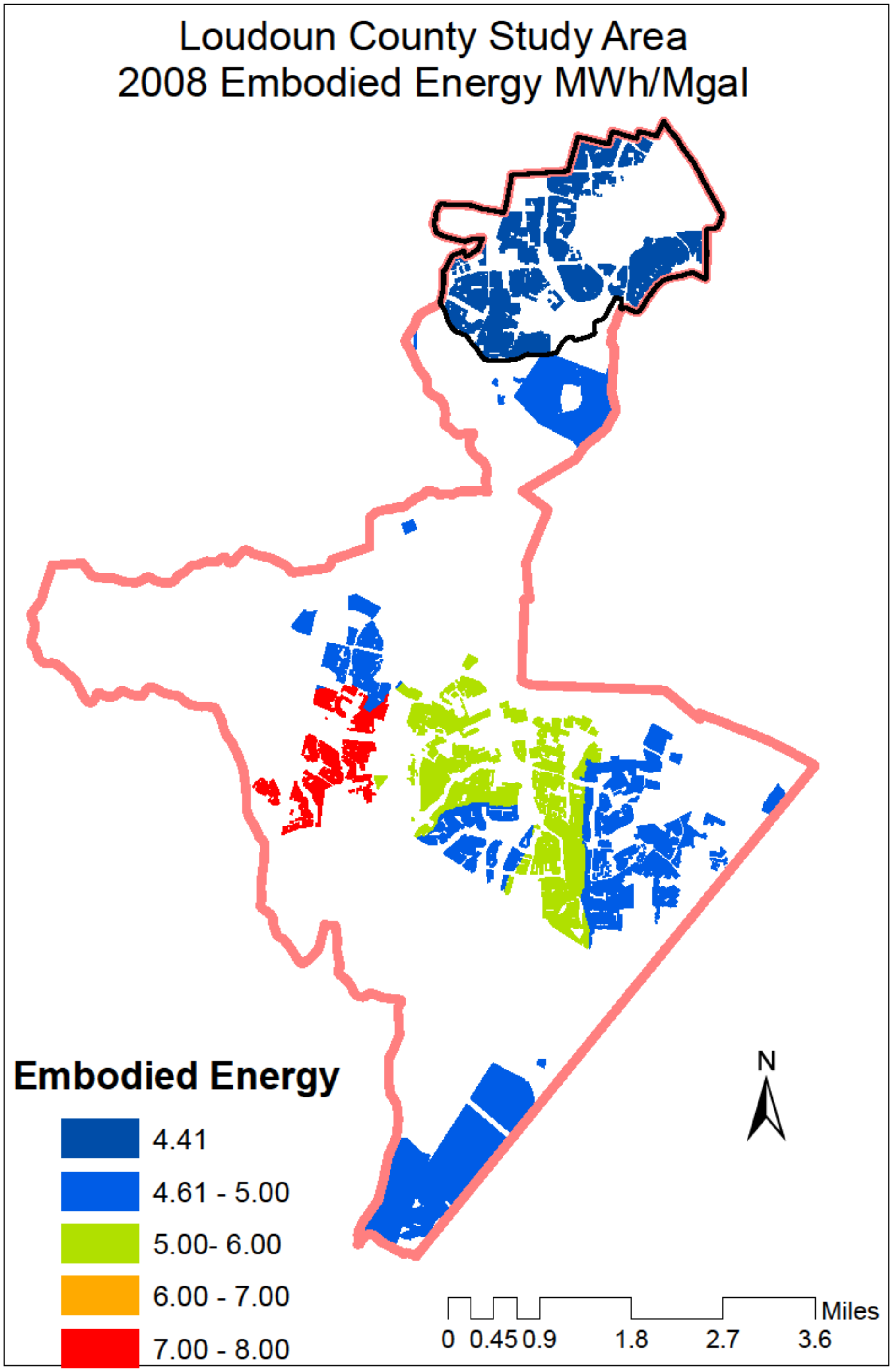


Figure 24: Embodied Energy for Study Area

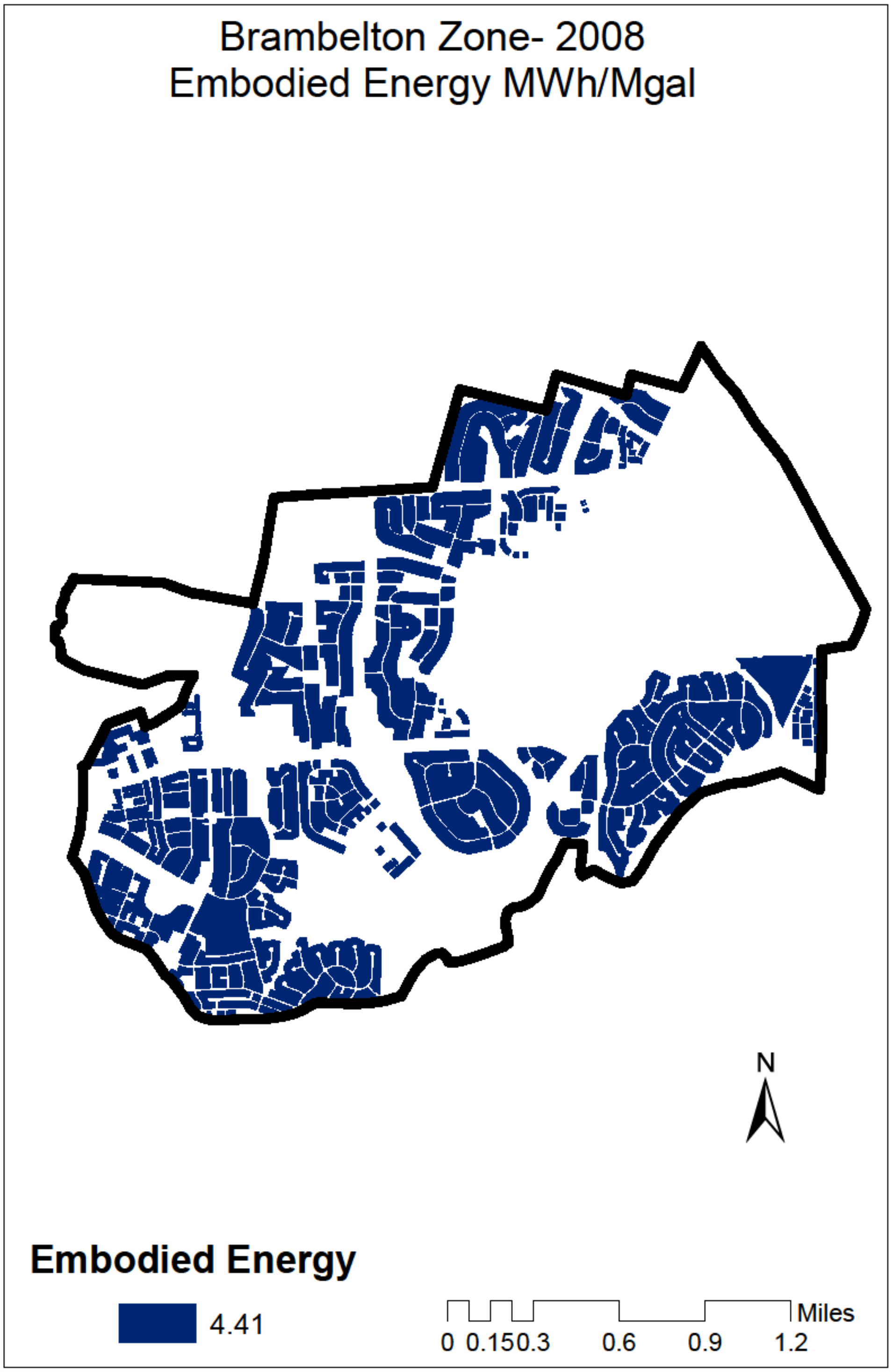


Figure 25: Embodied Energy for Brambelton Zone

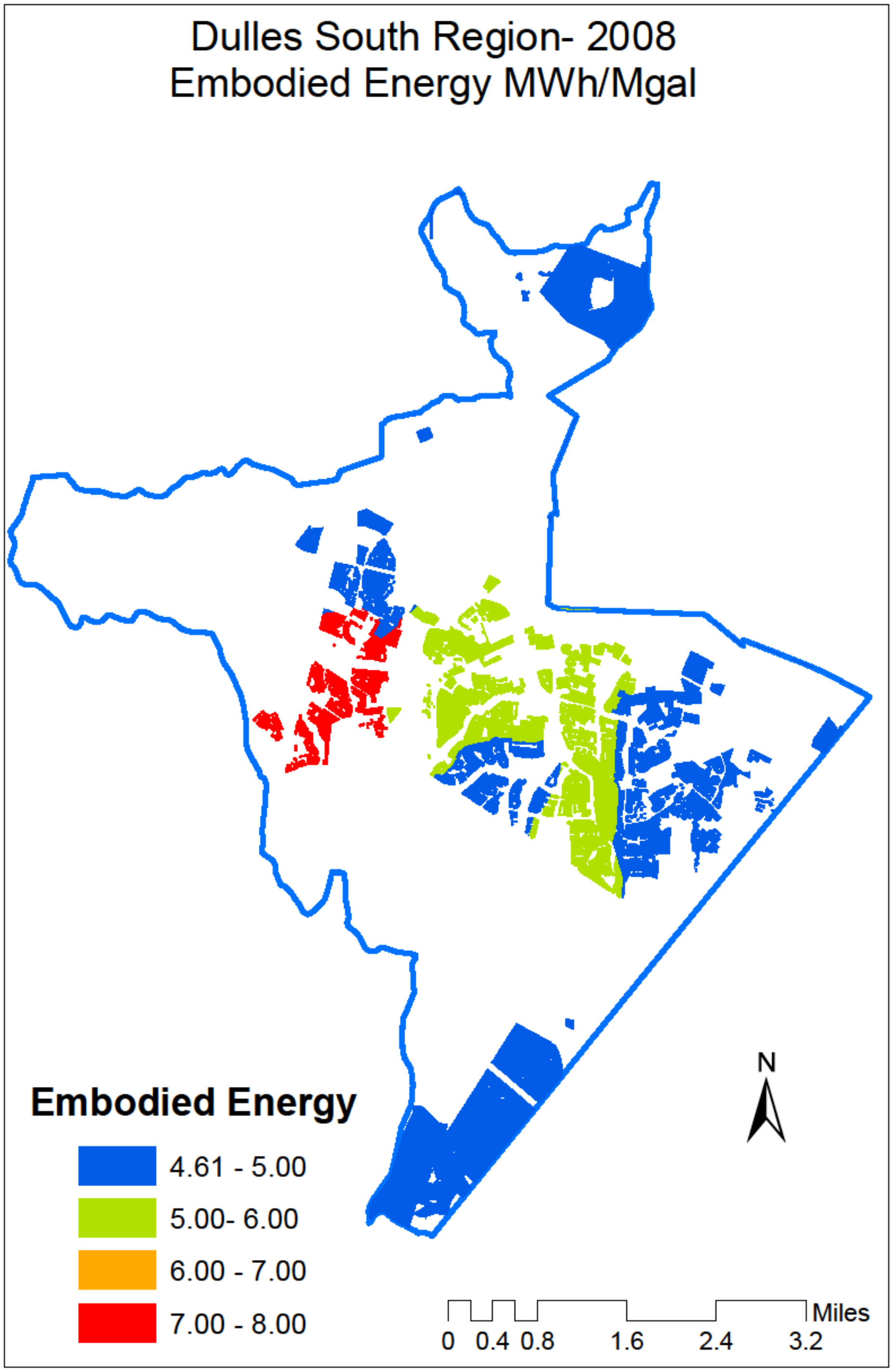


Figure 26: Embodied Energy for Customers in Dulles South Region

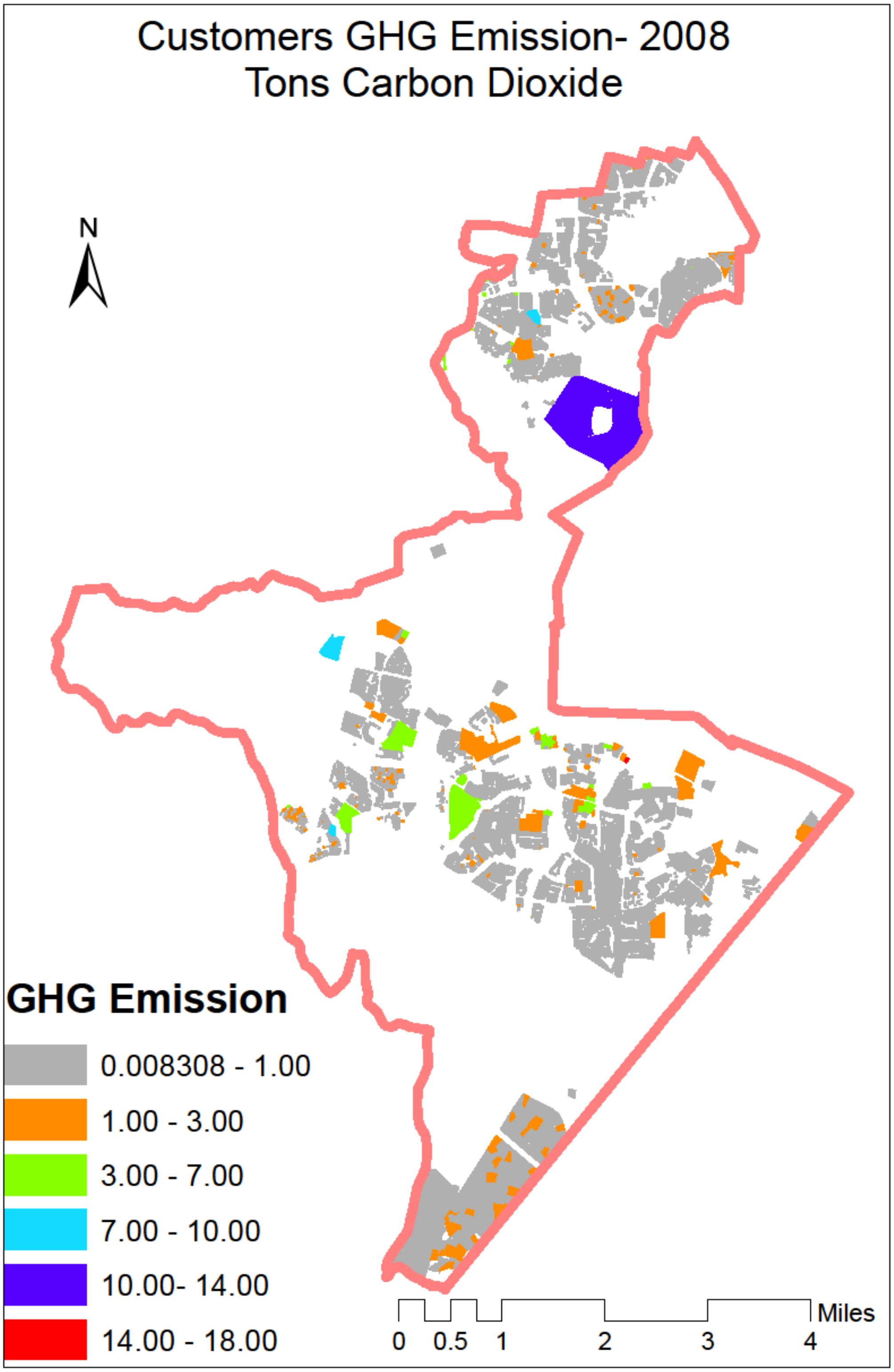


Figure 27: Carbon Footprint for Study Area

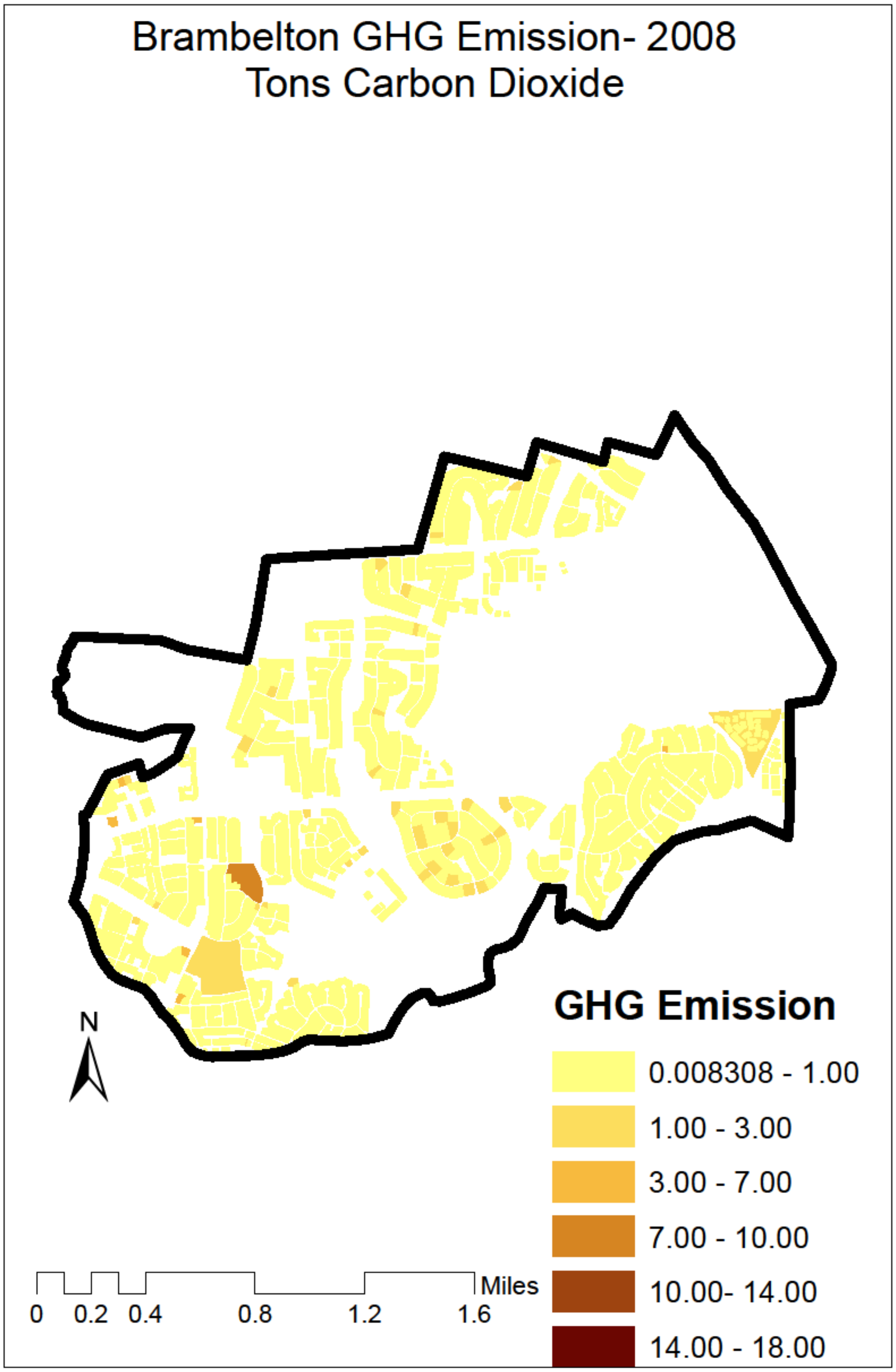


Figure 28: Carbon Footprint for Brambelton Area

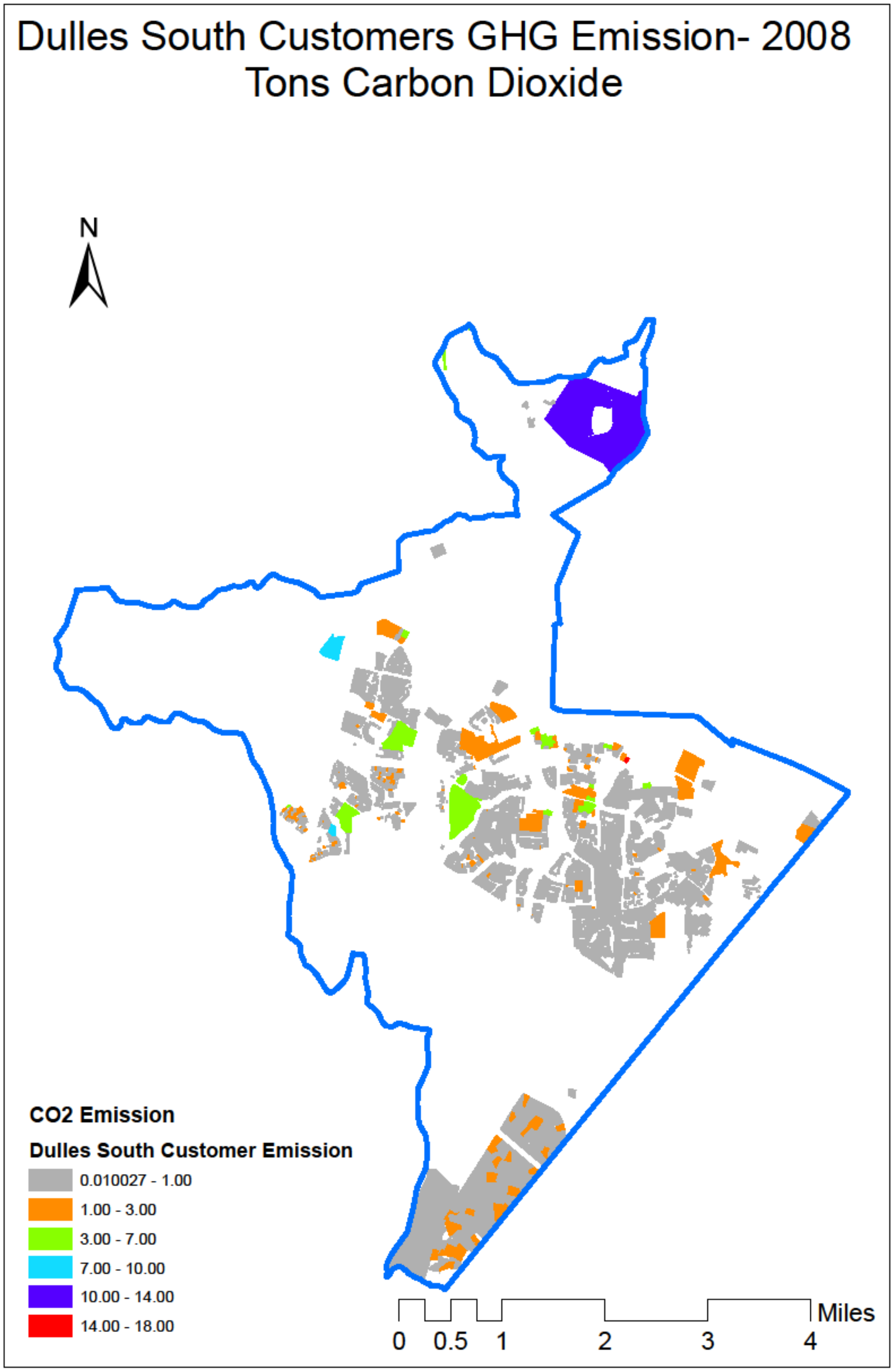


Figure 29: Carbon Footprint for Dulles South Region

A portion of the model output tables is presented in Appendix H. A graph of the Dulles South customer annual carbon dioxide emission against the water demand is shown in Figure 30. It reveals a linear relationship of end use water consumption and the emission contribution. The regression analysis of output values for the Dulles South Region determined a slope of 2.62 for the Emission-Water Demand graph. For a million gallon of water consumption by a customer located in Dulles South region, one can expect at a minimum 2.62 tons of carbon dioxide emission to be generated. This shows the importance of the demand side water conservation in reducing carbon footprint. In the same token, Figure 31 revealed a slope of 5.13 for the Energy Use-Water Demand graph. One million gallon of water consumption for a new development in Dulles South region could consume a minimum of 5.13 MWh of energy. The following equations may be used to predict demand side water system environmental impact in year 2008 in Dulles South Region. Appendix I provide the statistical analysis for the regression of data points. There is a high linear correlation relationship among the variables for two graphs.

$$\mathrm{ENER} = 5.13 \left(\frac{\mathrm{MWh}}{\mathrm{Mgal}}\right) \times \mathrm{WD} \qquad \text{(Eq. 19)}$$

$$\mathrm{EMISS} = 2.62 \left(\frac{\mathrm{TonsCO2}}{\mathrm{Mgal}}\right) \times \mathrm{WD} \qquad \text{(Eq. 20)}$$

Where:

ENER= Annual energy consumed to deliver water to end user (MWh/yr)
EMISS= Annual emission resulted from delivered water (Tons CO_2)
WD= Water demand (Mgal/yr)

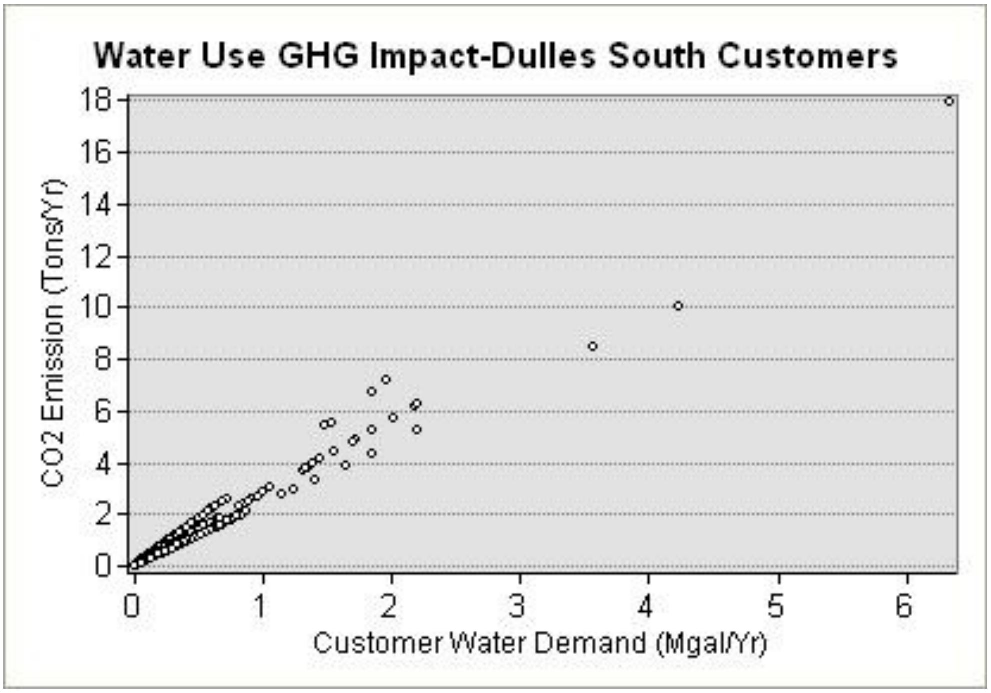


Figure 30: GHG Emission for Water Demand- Dulles South Region Customers

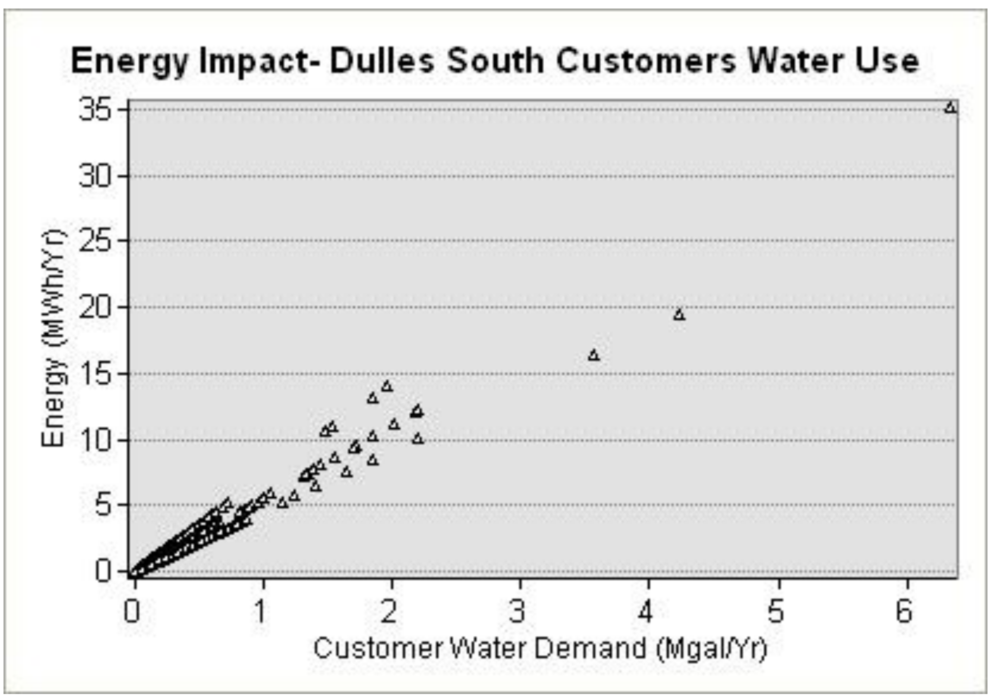


Figure 31: Energy Use for Water Delivered to Dulles South Customers

Table 16 shows the embodied energy and emission intensity matrix for each disaggregated data and segment of the water cycle for the Dulles South region, and the Brambelton area. The results can be updated annually and a historical track record for the water cycles environmental metrics may be maintained. This provides for a track record of the variance on the embodied energy and the emission as energy conservation efforts are implemented. Intensities can be determined through additive segment intensity matrix. This framework facilitates studies of embodied energy at any region. In a typical geographic area, the intensities for the water and wastewater treatment do not show significant variability assuming no major infrastructure or treatment process changes, due to a fixed source of water supply, and maintained effluent regulations. However, energy intensities for distribution segment for each customer can significantly vary depending on where he resides in the county. For a customer living in the Dulles South region, on average 25 percentage of embodied energy is attributed to water treatment, 5 percent to water distribution, 25 percent to wastewater treatment, and 45 percent to sewer collection. This implies a very interesting observation that more energy is devoted to treatment of wastewater and collection (70% of total amount) compared with the water treatment and conveyance segments.

Consideration of alternate smaller wastewater treatment systems such as decentralized treatment could result in a lesser embodied energy for Loudoun Water when compared with existing central and advanced tertiary treatment by the municipality.

Table 16: Loudoun Water Embodied Energy and GHG Emission

Water Cycle Segment	Loudoun Water Embodied Energy and GHG Contribution for Study Period: 2008			
	Brambelton Zone		Dulles South Region	
	Embodied Energy MWh/Mgal	Emission Intensity Tons CO_2/ Mgal	Embodied Energy MWh/Mgal	Emission Intensity Tons CO_2/ Mgal
Water Treatment & Source Extraction	**2.31**	**1.13**	**2.31 (25%)**	**1.13**
Water Distribution	**0.28**	**0.14**	**0.49 (5%)**	**0.24**
Water Sub-Total	**2.59**	**1.27**	**2.8 (30%)**	**1.37**
Wastewater Treatment	**2.27**	**1.25**	**2.27 (25%)**	**1.25**
Wastewater Collection (Mean)	**0**	**0**	**4.10 (45%)**	**2.01**
Wastewater Sub-Total	**2.27**	**1.25**	**6.37 (70%)**	**3.26**
Total Life Cycle	**4.86**	**2.52**	**9.17**	**4.63**

A customer can visually identify the environmental impact of energy consumption as it relates to the delivered potable water. Figure 32 shows a subset of commercial customer parcels in Dulles South region. The red color parcels represent the maximum emission range of 6.18-17.93 tons per year for customers. Table 17 and Figure 33 shows the GIS output for a customer in Brambelton area. The embodied energy and carbon footprint was calculated for a customer in this region to be 4.41 Wh/gallon, and 7.0 tons of CO_2 per year for

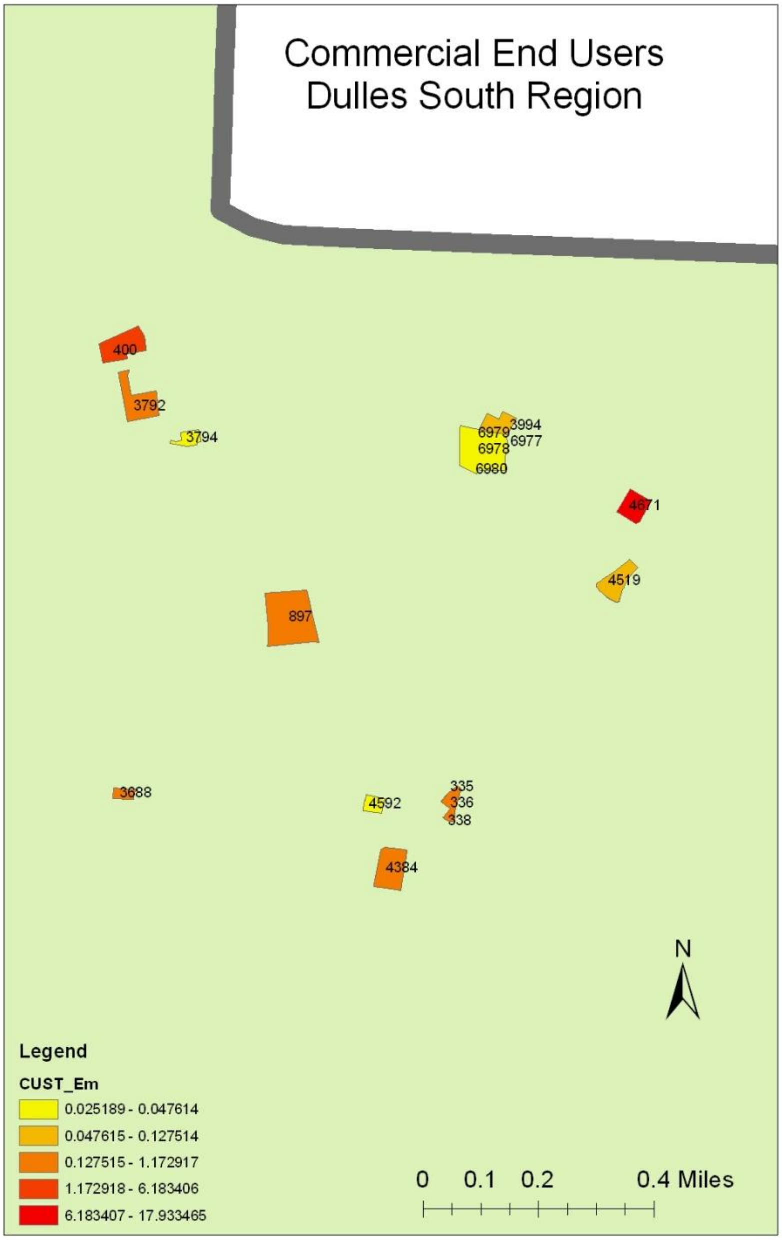


Figure 32: A Commercial Customer (OBJECT ID-4671) - Dulles South Region

Table 17: Customer Located in Brambelton Pump Distribution Area- GIS Output

CustPt_FID	Customer Flow, Mgal (CUST_WF)	Customer Sewer Flow, Mgal (CUST_WWF)	Customer Energy, MWh (CUST_E)	Customer Emission, Tons CO2 (CUST_Em)	Customer Embodied Energy, MWh/Mgal (CUST_EMB)
1523	3.09	2.48	13.65	7.02	4.41

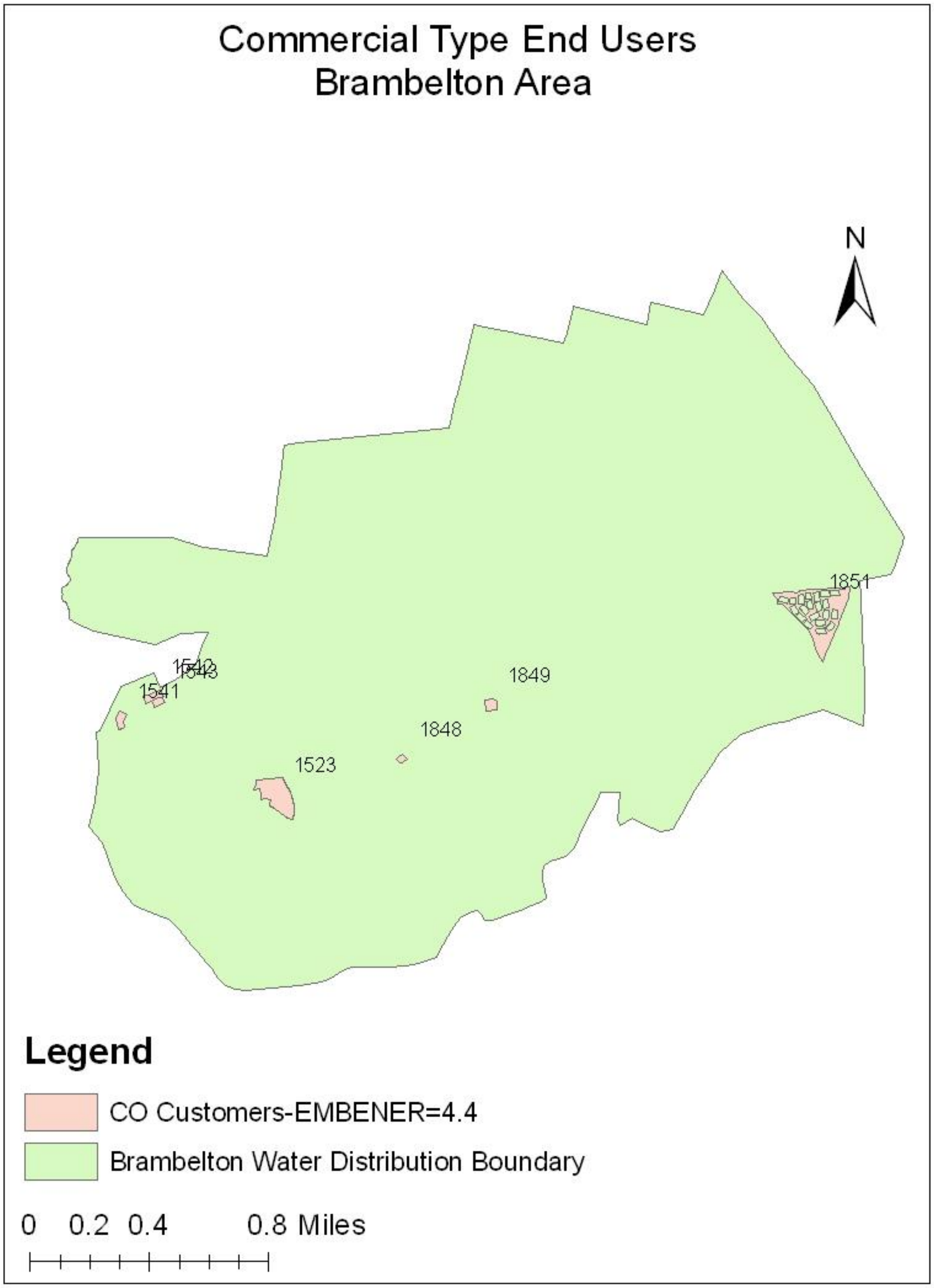


Figure 33: Commercial Customers inside Brambelton Zone

Carbon Footprint Estimation Model Validation

The GIS model for carbon footprint estimation of water cycle for Loudoun Water regions of study was tested and validated for output and input accuracy. The details of the validation work are presented in Appendix G. The validation is based on comparison of the total energy input into the water cycle against the model output quantity. The output is the sum of all aggregated energy attributed to all customers in a water cycle. A random sample of 61 end users was selected out of a total of 7,299 in the Dulles South region and the model output energy and the resulting GHG emission were compared with known quantities reported by municipalities. The output energy manually calculated matched the input value.

In addition, a subsystem of the water cycle, namely the water distribution pump embodied energy, was selected and the theoretical pump energy and embodied energy were calculated. The actual embodied energy input parameter was compared with the mean calculated theoretical value derived from a hydraulic formula. The actual measured embodied energy for the Brambelton pumps used as an input to the model was 0.28 MWh/Mgal. This compared favorably with the mean value (0.27 MWh/Mgal) obtained from the Brambelton zone hydraulic calculations on a set of end users. A deviation of 3.6% was noted.

CHAPTER 8 – SIMULATION

The strength of the GIS model lies in its ability to assist utility planners in making decisions regarding sustainable development. This chapter illustrates ways that this model might support a water utility, a customer, or a planner in operation support, energy and water consumption and conservation opportunities, and decision support for capital investment or locating facilities. A key capability of this model is to use spatial coincidence of features to assign new data, and also to use spatial relationship between features to select elements and assign new data. This new data layers can then support decision makers in their planning and infrastructure optimization. An important feature is the capability to vary basic thematic mapping by color coding the data by underlying attribute ranges. These maps can convey the results more clearly than presentation of tables and text. Energy and emission intensities for entire customer based coverage can be mapped based on selected criteria or constraints. More complex analysis or simulation may be performed such as locating potential sites for facilities. The following section presents several scenarios to test the model.

Queries and What-If Scenarios

Several hypothetical simulations were performed to illustrate the flexibility of the model to provide information to support the planning process. The following scenarios were modeled:

1. How can this model support the LEED rating system?

The USGBC Leadership in Energy and Environmental (LEED) rating currently does not address the embodied energy in water distribution even though it is one of the primary energy end use. This model can provide maps of energy consumption attributed to water distribution for a geographic region so it can be used for LEED rating system. For example a building situated on a real state parcel with a lower water cycle embodied energy compared to a benchmark value may be credited a point in the LEED rating system for the Sustainable Site category.

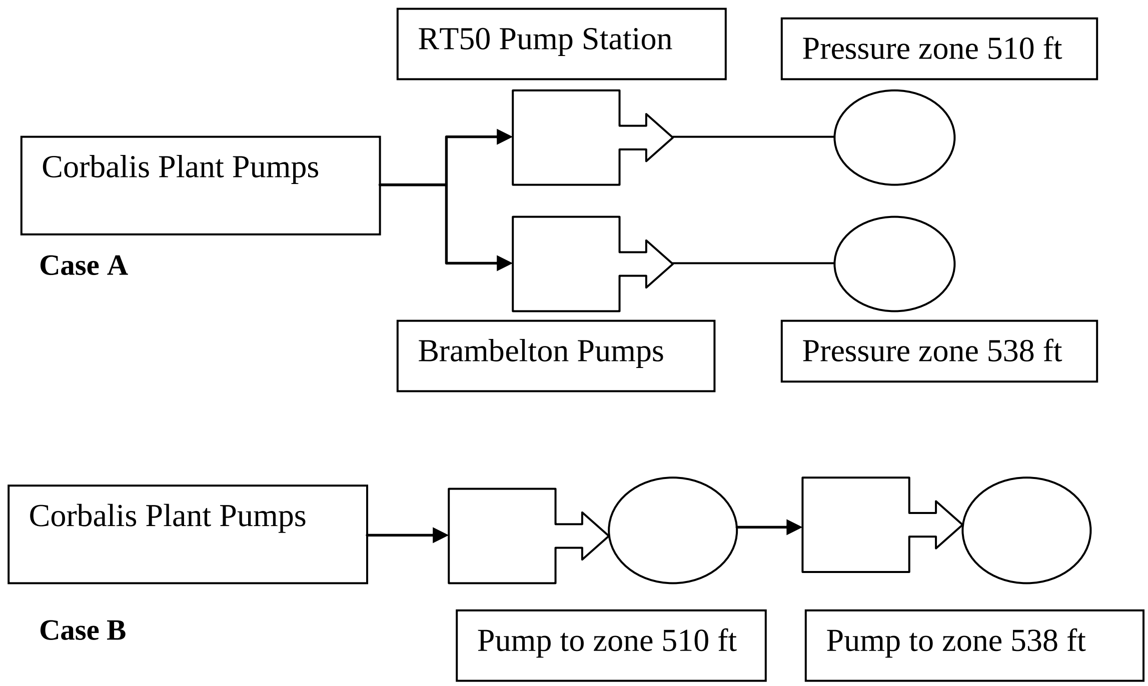
To demonstrate this capability, and to answer the question “What is the carbon footprint impact of customers in different pressure zones? “ two commercial customers were selected and analyzed from two different regions and pressure zones. Figures 32 and 33 in Chapter 7 show the results of the customer embodied energy.

Information visually observed on the maps is also provided in Table 18. The carbon footprint metric increases directly with the amount of delivered flow, and the energy consumed to provide that flow within a water cycle.

Table 18: GIS output showing two customers located in different regions

Customer ID	Region	Pressure Zone Feet	Demand Mgal/Yr	Customer Embodied Energy MWh/Mgal	Customer Annual CO_2 Emission Tons/Yr	Customer Annual Energy Consumption MWh/Yr
4671	Dulles South	510	6.34	5.55	17.93	35.19
1523	Brambelton	538	3.09	4.41	7.02	13.65

It is interesting to note that for this scenario, the selected Dulles South customer has a higher emission in spite of his lower water distribution pressure zone compared to the Brambelton customer. It also shows that one cannot automatically assume a higher carbon footprint for a customer who is located in a higher pressure zone without consideration to the pipe network layout. Water distribution is only one of the four components that affect the customer carbon footprint impact. The configuration of a water distribution network of a water cycle plays a key to realize the effect of a higher pressure zone in a water distribution segment. There are two pipe distribution configurations. The Corbalis Water Treatment Plant delivers the potable water to a vault, from which two separate pump stations (RT50 and Brambelton) distribute the flow to different zones. Case-A diagram shown below depicts this pipe distribution configuration. The embodied energy for water distribution to a higher pressure zone region would have been cumulative if it were Case-B configuration.



This simulation demonstrated that while building operation energy consumption and efficiency are significant to obtaining LEED credits, attention should be paid to the energy impacts associated with water use. Currently there are no credit categories for Sustainable Sites that weigh the environmental impacts of water delivery, specifically the embodied energy for delivered potable water. Based on the energy consumption requirements of the water resources alone, LEED should consider giving credit to buildings sited in locations that reduce the amount of embodied energy required to deliver potable water and treat wastewater. This means that buildings with lower water cycle embodied energy in a region have less of an environmental impact. A credit could be given for buildings sited at a similar geographical location in the region, just as a credit would be given for the selection of a Brownfield site.

2. **What sector in a region is the greatest contributor of the GHG emission? What is the impact of a residential customer location?**

It is critical to identify the most energy consuming sector in order to evaluate the proposed potential energy and water conservation measures. In this scenario, the Dulles South data output for energy consumption and GHG emission was categorized in terms of the customer type. Table 19 shows residential sector contributes 84% of total energy and GHG emission.

Table 19: Dulles South Emission and energy consumption per sector

Customer Type	Total Energy Use MWh/yr	Total GHG Emission Tons of CO_2/yr	Customer Count	Percent Total
Total	4,882.15	2,492.80	7,299	100%
Single Family Residential	4,102.07	2,094.27	7,089	84%
Commercial	445.05	227.27	148	9%
School	204.06	104.44	16	4%
Multi Family Apartments	58.16	29.58	16	1.2%
Church	0.637	0.327	5	0.3%
Others	72.16	36.91	25	1.5%

In order to find the environmental burden that the residential customers have in a region due to their geographical location, all customers with the same water demand magnitude (0.1 - 0.137 Mgal/yr range) and the highest embodied energy value from the Brambelton and the Dulles South were selected. The result of the GIS output analysis is shown in

Table 20. A higher embodied energy for a customer at a fixed water demand results in a higher GHG emission and energy use.

This result can be further compared with the average US household energy use for home appliances. Table 6 in Chapter 3, shows the compact florescent 20 watt lighting source consumes the highest energy (0.44 MWh/yr) in US homes. The energy consumed in 2008 to furnish the municipal potable water to selected (1,054 counts) homes in Loudoun County is found to be higher (0.63 MWh/yr- average) than the lighting fixture source. A customer's water consumption contribution to GHG emission is on average 0.32 tons of carbon dioxide.

The result also underscores the importance of a house location in a region where water consumption level is chosen to be irrelevant. All these users had an average 328 gallon per day water demand in 2008, and still had a sizable carbon footprint associated with their water consumption due to their geographical location. Water conservation for them may not greatly reduce their carbon footprint. The greatest impact is if their home were built in zones with lower embodied energy or when the initiatives by region's water and wastewater authorities to implement energy conservation or alternative decentralized treatment systems are realized.

Table 20: Embodied Energy Range-Residential Customers

Region	Users Embodied Energy MWh/Mgal	Users' Mean Flow-Mgal/Yr	Users' Mean Energy Consumption MWH/Yr	User's Mean Annual Emission Tons CO_2
Brambelton	4.41 (lowest)	0.12	0.51	0.27
Dulles South	7.20 (Highest)	0.12	0.83	0.41

3. Where a commercial zone should be placed inside a region? What would be a suitable place to locate a laundry facility?

Another application is to demonstrate that planning for a commercial/industrial zoning with high water users have significant energy and GHG emission implication. A benefit of this carbon footprint model is to enable a planner to zone a region based on its embodied energy characteristics. A laundry facility is a high water consuming commercial business. Assuming that there is no water reclamation facility for the laundry facility, a suitable geographical area within the study coverage can be explored with the following criteria:

- Within a sewershed zone with a gravity type wastewater collection
- Having the lowest pressure zone in the county
- Closest to a major highway
- Having water and wastewater service connections

Using the GIS model for the Dulles south and the Beambelton areas, the lowest pressure zone (510 feet) is assigned to Dulles South Region. Within the Dulles South region, commercial zones were identified. The candidate sites closest to a major highway can also be observed. Parcels with a water service connection are then selected. The selected parcels are overlaid with the map of Dulles South showing the embodied energy range. A parcel can then be identified that meets all the criteria. The following are the steps taken in the GIS spatial analysis:

- Select all commercial customers inside Dulles South region
- Select all customers with criteria WWpumpEMB=0
- Turn on topography map and World Imagery layers to identify major roads
- Turn on Sewer network layer to identify parcels with service connection
- Select parcels near major road and create a layer file

Table 21 shows the best candidate parcels for placement of a laundry facility:

Table 21: Suitable Candidate Parcels for Laundry Facility

Parcel Object ID	Parcel Acre	Customer Embodied Energy MWH/Mgal	Customer Energy Intensity Tons CO_2/Mgal
512- 513	18.49	4.6	2.62
2408	2.40		
2465	1.64		
2466	1.44		
2467	1.45		
2468	1.86		

The maps in Figures 34 and 35 shows the cluster of proposed parcels off Route 50 and near the residential community with lowest customer embodied energy potential (4.6 Wh/gal), and customer energy intensity of 2.62 Tons CO_2/Mgal. The parcel is provided with an 8-inch diameter sewer line. Knowing the laundry facility water demand magnitude, its carbon footprint can be predicted by applying the determined energy intensity metric:

$$\text{Predicted GHG} = \text{WD} \times \text{EI}$$

$$\text{End User CF} = 2.62\,\frac{\text{Tons}}{\text{Mgal}} \times \text{WD}$$

Where:

GHG= greenhouse gas (Tons CO_2)
CF= Carbon footprint (Tons CO_2)
WD= Water demand (Mgal)
EI= Energy intensity (Tons CO_2/Mgal)

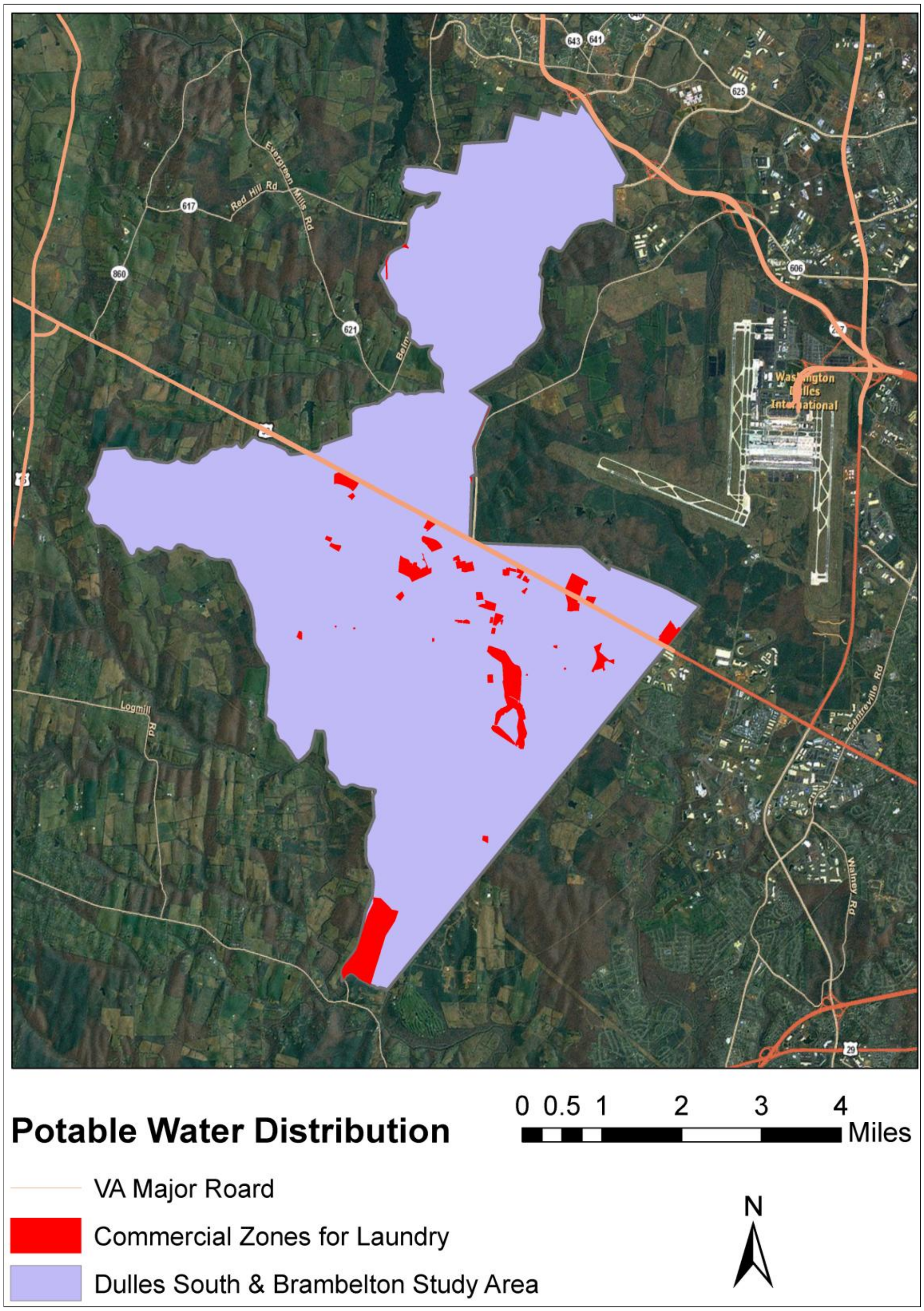


Figure 34: Selected Parcels with a Set of Criteria

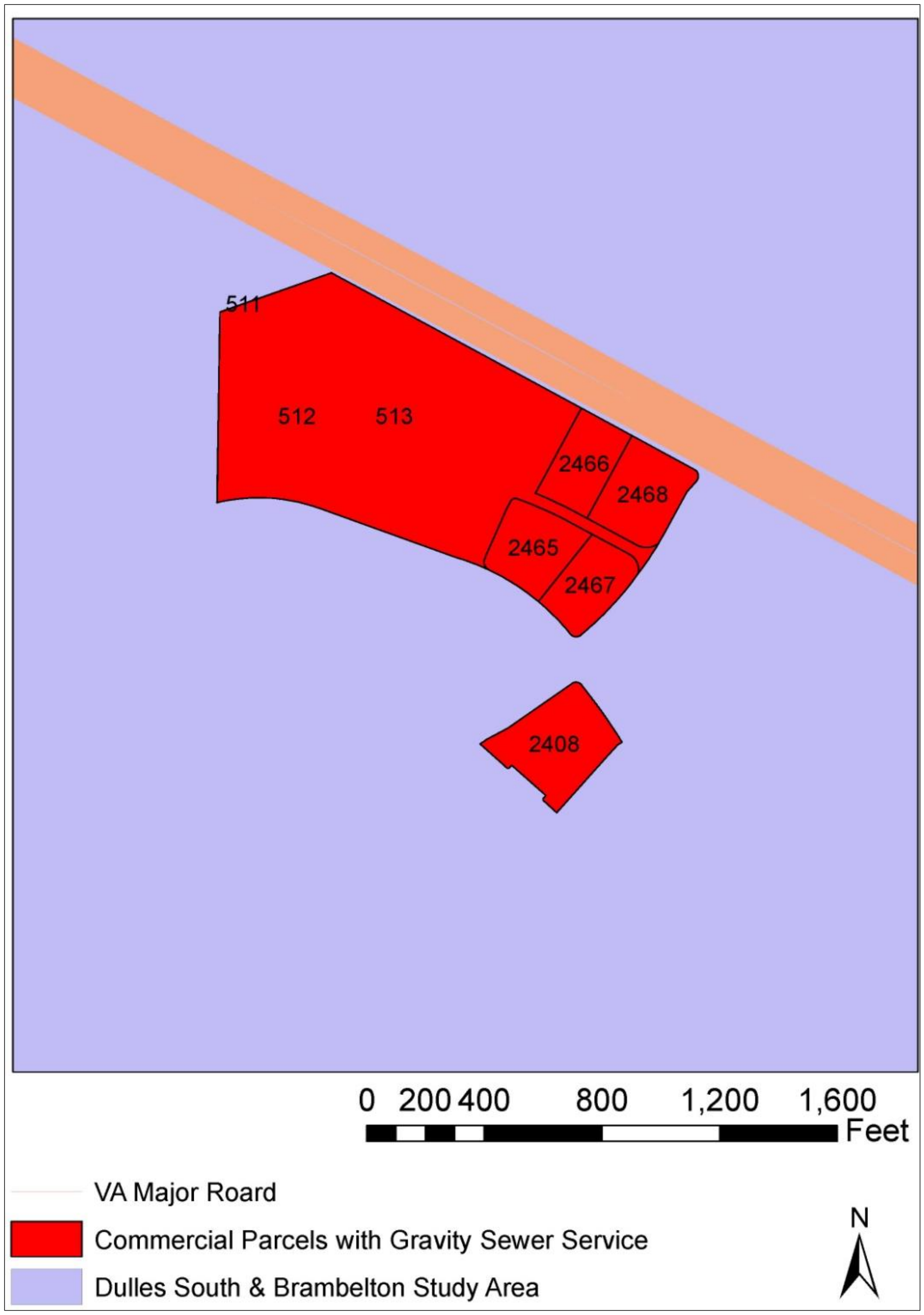


Figure 35: Selected Parcels for Proposed Laundry Facility

4. What is the impact on GHG emission from locating a county wastewater treatment Plant? What would be alternatives to realize a low carbon footprint?

A review of the water cycle for the Dulles South region revealed the second highest embodied energy in the water cycle is attributed to wastewater treatment with a magnitude of 2.27 MWh/Mgal. One option to consider is to construct a smaller community wastewater treatment plant, thus reroute the Loudoun County sewer to the new smaller plant inside the county in lieu of the Blue Plains wastewater treatment plant in Washington DC.

Figure 37 shows the proposed location of a contemplated new advanced wastewater treatment plant for Loudoun County (designated by a cross). It also reveals the Dulles South area relative to the Blue Plains wastewater treatment plant in Washington. The collected sewer is delivered via a combination of 171,066 feet long gravity pipeline (Potomac Interceptor) and 33,000 feet long forced main to Blue Plains. The sewer flow profile is shown in Figure 36. A proposed alternate wastewater treatment plant should treat the peak flow of 16 MGD. Considering an embodied energy of the new treatment plant to match the national average of 1.70 MWh/Mgal for an advanced treatment with nitrification, the Dulles South water cycle total embodied energy can be reduced. In fact it would reduce the existing embodied energy for the wastewater treatment by 25%. The impact of this change for wastewater treatment segment on a customer was calculated using the model. Table 22 shows the parameters to be used in the GIS model to determine all customers' GHG emission.

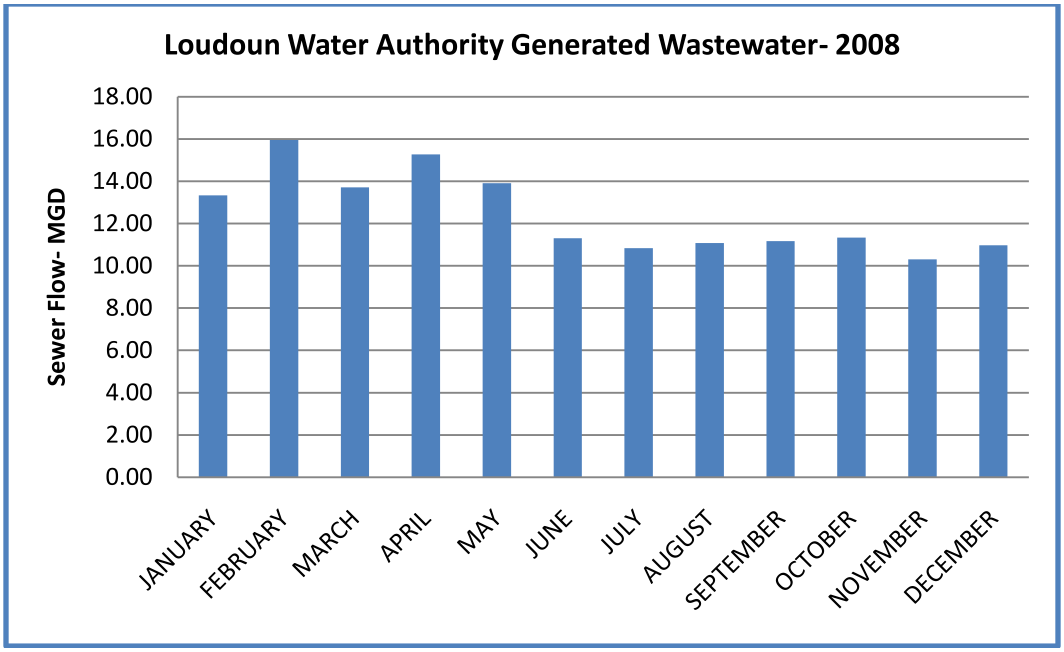


Figure 36: Loudoun Wastewater Flow Carried by Potomac Interceptor

Table 22: Emission Impact-Proposed Wastewater

Name	Flow Mgal/yr	Energy Used MWh/yr	Embodied Energy MWh/Mgal	Emission Coefficient Metric Tons CO_2/MWh	Emission Intensity Tons of CO_2/Mgal	Emission Tons CO_2
New WWTP	4,531.7	7,703.90	1.70	0.49	0.83	3,774.91

The impact of a new wastewater treatment plant on customers is shown in Table 23, and 24. The customer overall water cycle embodied energy and emission is reduced by 7% and 16% respectively.

Table 23: Customer Emission Impact at Lower Embodied Energy

Customer ID 4671	Customer Annual Energy Use MWh	Emission Intensity Tons of CO_2/Mgal	Power Generation Emission Coefficient Metric Tons of CO_2/MWh	Customer Annual CO_2 Emission Tons of CO_2 per year	Annual Drinking Water Demand Mgal	Customer Embodied Energy MWh/Mgal
Exist. Water Treatment	14.64	1.13	0.49	7.17	6.34	5.14
Exist. Water Distribution & Conveyance	3.40	0.24	0.49	0.81		
New Wastewater Treatment	8.62	4.21	0.49	4.23		
Exist. Sewer Collection	5.93	0.58	0.49	2.90		
Total	32.59	5.86		15.11		

Table 24: Percent Changes in Customer Embodied Energy- Dulles South

Customer ID	Wastewater Plant	Water Treatment Plant	Water Demand / Sewer Flows Mgal/Yr	Customer Embodied Energy MWh/Mgal	Customer Annual CO2 Emission Tons/Yr	Customer Annual Energy Consumption MWh/Yr
4671	Blue Plains	Corbalis	6.34/5.07	5.55	17.93	35.19
4671	New WWTP	Corbalis	6.34/5.07	5.14	15.11	32.59
Percent Reduction				-7%	-16%	-7%

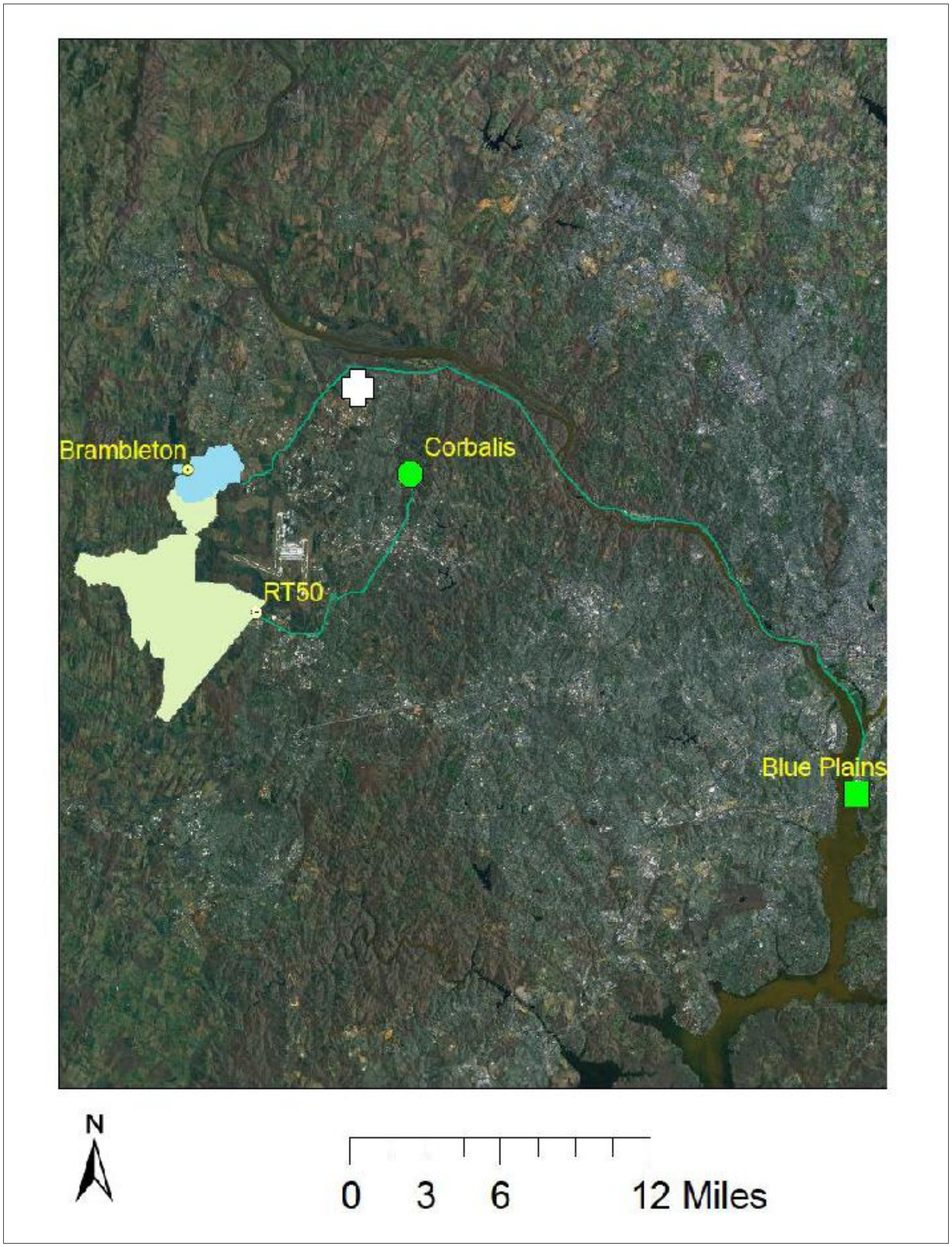


Figure 37: Alternate location - Wastewater Treatment

Embodied Energy Estimation Analysis & Application

The model output can show the variability of customer embodied energy within two major segments of the water cycle, namely water distribution, and wastewater collection. Future expansion of the model can build variability into the other segments taking into consideration typical treatment technology for treatment plants, sources of raw water intake for its geographical or jurisdictional location. Information on a proposed location for new treatment plant, projected energy consumption for treatment processes, flow quantity and water distribution alternative schemes can be entered into the model and its projected carbon footprint results can be compared. The GIS based approach provides a simple concept to facilitate decision making on the basis of carbon footprint intensity when more than one alternative is encountered.

The level of disaggregation build into water distribution and sewer collection segments determines the level of variation of energy consumption geographically. It is broken out on the basis of pump station location and actual energy use which inherently accounts for its topography including lift, distance, and other energy consuming elements for infrastructure. This approach facilitates a GIS technician to delineate the customer zones based on the service connection to water pumps and lift stations within a sewershed area. A varying topography translates into multiple pump stations within a region that is indicative of higher energy intensive region and thus potentially higher embodied energy to deliver water to customers within that region. Developing representative energy intensity for various topographies within a county can assist mapping of high energy and low embodied energy zones. Embodied energy data within a region, or county may be cataloged on the basis of its defined topography (flat, moderate, hilly), and its treatment plants types. Cross referencing the embodied energy magnitude with each region of interest within a county with the relative energy intensities of treatment plants provides valuable information to aid decision making in water infrastructure optimization and future water studies by environmental engineers and research institutions. Table 25 and Table 26 show proposed catalog of regions' embodied energy and other relevant indicators.

Table 25: Representative Embodied Energy for Regions in a County

Defined Jurisdiction				Total Life Cycle Embodied Energy
Zones	Water Basin	Electric Utility	Region	MWh/ Mgal
RT 50 Pump House	Potomac River	Dominion VA Power & Pepco	Dulles South, Loudoun, VA	9.17
A zone in Brambelton Pump House	Potomac River	Dominion VA Power & Pepco	Brambelton, Loudoun, VA	4.86

Table 26: Proposed Catalog Continuation

	Treatment Plant Type and Capacity		Water Pressure Zone
Zones	Water	Wastewater	Ft
RT 50 Pump House	Surface Water Supply; 150 MGPD	Advanced Treatment; 370 MGPD	510
A zone in Brambelton Pump House	Surface Water Supply; 150 MGPD	Advanced Treatment; 370 MGPD	538

Comparison of Results with Average US and Canadian Values

The result of this research study was compared with the national average values. The estimated average energy intensity is based on information presented in a 2002 study by EPRI. Table 3 shows the US average values of energy use. It should be noted that energy consumption values obtained under this research study included of all energy use for operating the treatment facility. It was inclusive of energy of treatment processes, the facility buildings' lighting, ventilating, heating and cooling systems, thus representing the actual energy consumption for operating a water cycle within a study area. Table 27 shows that in general, the embodied energy for wastewater treatment segment of the Dulles South was higher compared to the Canadian study (Table 4) and the US average values. One reason for a higher embodied energy in this case is due to increased effluent quality that is discharged into the Chesapeake Bay.

Table 27: Comparison with US Mean Results- EPRI[15]

	Treatment Plant size	Unit Energy Consumption – MWh/Mgal	
		Advanced Wastewater Treatment with (Nitrification)	Surface Water Treatment
National	Average (POTW)	1.91	1.41
Dulles South Area (370 MGPD WWTP; 150 MGPD WTP)		2.27	2.31

[15] Water & Sustainability, Vol. 4, The Next Half Century, Topical Report, March 2002

The studies indicate that there could be a wide variation in embodied energy for the entire water cycle from one region to another because of variability of many factors influencing this environmental indicator. Thus a significant opportunity exists for energy savings and GHG reduction by incorporating the embodied energy of water and wastewater into environmental rating programs, municipal decision-making, and energy reduction programs.

An interesting observation of the comparison of the Dulles South region embodied energy (2.27 MWh/Mgal) for the wastewater treatment segment with the national mean value (1.91 MWh/Mgal) is the opportunity that exists in lowering the magnitude of this metric for Loudoun County. Considering implementation of alternative sustainable on-site wastewater treatment schemes could result in a lower embodied energy for this water cycle. Loudoun County wastewater flow to the Blue Plains wastewater treatment plant was 13.8 million gallons per day (4% of total flow) in 2008.

Construction of alternative wastewater treatment such as Living Machine[16] could be considered for management of partial flows generated in Dulles South Region. A Living Machine is an advanced biofilter that is designed to treat wastewater on site. Unlike chemically based systems, Living Machines incorporate bacteria, plants, snails and fish that digest organic pollutants. A typical Living Machine process include: anaerobic septic tank, anoxic reactor, closed aerobic tank (with plants to filter gases), open aerobic

[16] Source: http://www.livingmachines.com/htm/livtech.htm

tanks (with snails, shrimp and fish), composting, indoor effluent treatment via a wetland, and final discharge to the environment. This natural bio filtering design removes nitrogen and phosphorous to meet limits set by the State of Virginia to help protect and improve the water quality in the Chesapeake Bay. A major benefit of this alternate wastewater treatment is to lower energy consumption and the greenhouse gas emissions compared with the conventional treatment systems.

CHAPTER 7- CONCLUSION

The reviewed literature focused on the life cycle assessment of water and wastewater treatment processes. While many researchers utilized or recommended energy consumption as a sustainability indicator for water supply and wastewater treatment systems, there is a gap in the analysis of total water system energy use contributing to the carbon footprint of water utilities. Carbon footprint is a better indicator of sustainability than energy consumption because it accounts for the source of the energy consumed by a water system. Energy provided by a renewable source is comparatively more sustainable than energy from a non-renewable source. In order to make recommendations for the development of a total water system carbon footprint model, this research first presented a brief review of currently available sustainability rating systems and carbon footprint calculators. The literature review suggests that the embodied energy in both water and wastewater treatment is highly variable depending on the nature of the treatment plant. Similarly, the energy expended in the collection and distribution of water and wastewater depends heavily on the topography of the service area. The embodied energy in delivered water is currently not considered by the rating systems such as the USGBC LEED rating system. While building operation energy consumption and efficiency are significant to obtaining LEED credits, there is no attention paid to the energy impacts associated with water use. There are no credit categories for Sustainable Sites that weigh the environmental impacts of water delivery, specifically the embodied energy for delivered potable water. Based on the energy consumption requirements of the water resources alone, LEED should consider giving credit to buildings sited in locations that reduce the amount of embodied energy required to deliver potable water and treat wastewater. This means that buildings that require less water system pumping to receive potable water and have access to gravity driven wastewater collection systems have potentially less of an environmental impact than buildings situated higher in elevation to the water treatment plant and lower in elevation to a wastewater treatment facility.

Based on the review of existing sustainability tools, this research presented suggestions for the development of a GIS based model that estimates the embodied energy and corresponding carbon footprint of electricity consumption per gallon of water used for the municipal water and wastewater utility life cycle. An important step in emission reduction is to establish a consistent index and a standardized carbon footprint metric that includes the embodied energy for collection, treatment and distribution. Benefits to be derived from a standardized approach include: (1) Improved cost and benefit analysis in the decision process for real estate developers, building construction architects and engineers; (2) Improving energy use reporting and reduction schemes based on carbon footprint scheme; (3) Establishment of a recognized benchmark for use in the comparison, tracking and monitoring of emissions as it is attributed by the water and wastewater treatment and distribution; (4) Ability to quantify relative impacts of building design options using carbon emission equivalents.

This research developed a viable geographic information system (GIS) based carbon calculator tool for use by municipalities that have ArcGIS, version 9.2 for asset management of their infrastructure. The output of this model may be relayed to planners that estimates the tons per year of carbon dioxide equivalent for commercial, industrial, and residential building water use. This estimate includes the embodied energy requirements needed to collect, treat, and distribute water and wastewater. This model can be used to evaluate the environmental impact of proposed and existing facilities within a geographically identified water cycle.

The estimation of energy consumption and subsequent carbon footprint calculation relies not only on the quantity of water being distributed but also the geography of the distribution and collection network. Critical variables that play a significant role in the determination of the energy consumption were investigated. A GIS dataset for two specific regions were used as a case study in order to develop and test the model. This approach converts the annual water and wastewater needs for a system into tons of carbon dioxide per year. This tool answers critical questions related to the impact of demand side sustainable water practices on the comprehensive carbon footprint. In developing the model, components were defined for water treatment, water distribution, wastewater treatment and sewer collection segments of the entire water life cycle. It could prove to be a capable tool for performing the carbon footprint estimation algorithm.

This research is a starting point to reveal critical elements in construction of a GIS based model. Important spatial factors such as pressure zone, service zone elevation and distance to the treatment plant are critical elements that significantly affect the predication of embodied energy in potable water. The impact of these variables is captured within the water distribution and sewer collection boundaries and zones for the case studies. Spatial factors were considered in predicting the embodied energy in potable water for specific geographic areas namely, Dulles South and Brambelton regions. ArcGIS Desktop Application tool is suited to handle this type of analysis. For a large geographic area, GIS application is a key tool that has the ability to handle the different subsystems and their physical traits.

This research provided a benchmark for embodied energy of delivered water by municipalities to customers in Dulles South region of Loudoun County, Virginia. Embodied Energy, as an environmental indicator, can be used for assessment of LEED credit by USGBC. For example, a LEED credit can be assigned for an attempt to reduce embodied energy of delivered water to a new real estate development in comparison with the established benchmark inside the Dulles South region. In order to accomplish this objective, one or all of the following mitigations may be considered:

- A customer may purchase renewal energy from his/her power utility company to offset the higher emission intensive water cycle

- A customer can opt to reduce his/her annual water consumption through conservation and use of rain water for irrigation purposes

- A developer may opt to choose a site for locating a water consuming enterprise that has a lower water cycle embodied energy compared with the region's benchmark

A municipality may realize opportunities to reduce its embodied energy magnitude by avoiding extensive conveyance of water to its customers. It could purchase electricity from renewable sources.

Sustainability analysis, taking into consideration the entire water cycle embodied energy, is not a common practice in water industry. The framework applied under this research to determine the embodied energy and potential global warming indexes for municipalities in Loudoun County can be expanded to cover the entire commonwealth. The resulted outcome can be utilized as the established benchmark for comparative assessments with similar facilities in the same geographical region.

In summary, the devised model was found to be a viable tool that provides visual identification of carbon footprint on maps. Application of GIS tool to calculate carbon footprint is found to be an effective way in development of a nationwide catalog of embodied energy as an environmental indicator for water cycle and to enable tracking of infrastructure annual energy and water use optimization efforts; however, the level of mission success and estimation accuracy depends heavily on the following factors:

- Availability of flow and energy consumption data on all segments of water cycle
- Availability of a demand side water consumption
- Availability of municipalities' comprehensive GIS geodatabase
- Implementation of the proposed approach as described in this research
- Collaboration of interdependent municipalities to collect data
- Formal agreements to protect and secure water infrastructure data

Although this estimation was based on the water consumption on a parcel of land, it is related to the building(s) on its site. Energy performance for building, such as Portfolio Manager rating, usually accounts for water heating, but it should be extended to include the energy required to deliver the potable water (from municipality when applicable) to the building as well. This research developed an approach for a more comprehensive prediction of building energy performance and rating by DOE and EPA. Embodied energy (MWh/Mgal) and carbon footprint indicator (Tons of CO_2/SF) factors for delivered water may be used for a specific region in rating of the building energy performance.

Future Research

This case study determined the results of energy consumption and carbon footprint in 2008 as a snap shot look in time. Further application of the model for regions of the county is needed to establish a GHG emission trends with time. EPA keynote speaker, Andy Crossland, at the Virginia Water Environment Association and the American Water Work Association Joint Annual Meeting (WaterJam 2009) held in Richmond Virginia called for an improved asset management system in water and wastewater industry. The devised GIS model can serve as a template toward development of such undertaking.

The embodied energy is about 9 MWh/Mgal for the Dulles South water cycle. How does this region rank compared with other regions in Loudoun County, Virginia? The model should be expanded to include all regions of the County. The model should also be implemented nationally to estimate GHG emission at various utilities to fully explore its benefits and the limitation of the model. It is hoped that future extension of this research would lead to development of a comprehensive catalog of embodied energy of delivered water by municipalities nationwide. More research could lead to the development of a parameter that relates distance and change in elevation to energy consumption associated with the life cycle of the water system in specific regions. The empirical parameter might be used as an alternative method to predict the carbon footprint of delivered water and collected wastewater for evaluation of building energy performance in a region.

Appendix A: Pepco Power Company Environmental Information

MD 6/09 RG 01-21

This disclosure is required by the Maryland Public Service Commission

Environmental Information for Standard Offer Service Provided by Pepco

The following environmental information is for Pepco customers with Standard Offer Service. Standard Offer Service is provided to those customers who have not chosen an alternative electricity supplier.

Power plants can generate electricity from a number of different fuel sources, resulting in different emissions. Pepco will report fuel sources and emissions data to customers twice annually, allowing customers to compare data among the companies providing electricity service in Maryland.

The standardized environmental data provided are for January 1, 2008 through December 31, 2008.

For additional information, visit our Web site at pepco.com.

pepco

A PHI Company

Energy Source (Fuel Mix)
January 1, 2008 – December 31, 2008

Coal	54.2%
Gas	6.5%
Nuclear	34.1%
Oil	0.3%
Hydroelectric (> 30MW)	0.5%
Renewable Energy	
Captured Methane Gas	1.2%
Geothermal	0.0%
Hydroelectric (< 30MW)	0.6%
Solar	0.0%
Solid Waste	1.8%
Wind	0.5%
Wood or other Biomass	0.3%
Unspecified Renewable	0.0%
Total	**100%**
Renewable energy sources subtotal:	4.4%

Air Emissions

The amount of air pollution associated with the generation of electricity production for Pepco and for the Mid-Atlantic region is shown below.

Pounds Emitted per Megawatt Hour of Electricity Generated

	Pepco	Mid-Atlantic Regional Average
Sulfur Dioxide (SO_2)	7.0	7.0
Nitrogen Oxides (NO_x)	2.0	2.0
Carbon Dioxide (CO_2)	1,220	1,220

CO_2 is a "greenhouse gas," which may contribute to global climate change. SO_2 and NOx released into the atmosphere react to form acid rain. NOx also reacts to form ground level ozone, an unhealthful component of "smog."

152-03-09/PepcoMD-6_09

Appendix B: DATA Collection Questionnaire template

Wastewater Treatment and Collection Systems Questionnaire	Researcher: Ali Bakhshi; Email: abakhshi@gmu.edu
Fairfax County Wastewater Collection Division	Research Advisors: Prof. S. deMonsabert, sdemonsa@gmu.edu George Mason University Department of Civil & Environmental Eng

1. Please provide the name, title, and telephone number of the person to contact for information regarding this survey:

Name: ____

Title: ____

Telephone No.:____

Email: ____

2. Please provide information for your wastewater collection system for the most recent 12-month period for which data are available. Please specify the beginning and end dates for which data are provided.

____/____/____ to ____/____/____
(mm dd yy) (mm dd yy)

Collection System (Wastewater Treated at Norman Cole)

3. Please estimate the length of the collection mains piping in your system. Provide maps and boundaries of service if available.

Pipe Diameter (inches)	Pipe Length (miles)
____________	____________
____________	____________
____________	____________
____________	____________
____________	____________
____________	____________
____________	____________

____________	____________
____________	____________

4. How many people and connections does your system currently serve year round? Please indicate the number of people served by your system for all customer types that apply.

Customer Type	Connections	Number of People
Treatment provided for other public wastewater collectors	_________	_________
Residential	_________	_________
Non-residential		
Commercial/industrial	_________	
Agricultural	_________	
Other ________________	_________	_________
Subtotal, non-residential	_________	_________

5. How many collection Lift Stations does your wastewater collection system utilize?

Lift Station	Unique Identifier/ Name	Location (lat/long)	Is GIS available? Yes or No
L1	_______________	_______________	_______________
L2	_______________	_______________	_______________
L3	_______________	_______________	_______________
L4	_______________	_______________	_______________
L5	_______________	_______________	_______________
L6	_______________	_______________	_______________
L7	_______________	_______________	_______________
L8	_______________	_______________	_______________
L9	_______________	_______________	_______________
L10	_______________	_______________	_______________

6. How many Pressure Zones does your wastewater collection system have? Are the pressure zones and lift station locations available in GIS format?

7. Please enclose a map of your service area. We are specifically interested in GIS layers that include piping, service connections, pressure zones, and lift stations. Are GIS layers available?

Energy Consumption

8. What was your collection system's total energy consumption during the last year (as defined by answer in Question 2)?

___________ kWh

9. What was the cost of the energy consumed in $ per kWh during the last year (as defined by answer in Question 2)?

___________ $/kWh

10. Who is your collection system's energy provider?

11. Do you separately meter each Lift Station in your collection system? (circle one) Yes or No

If Yes, what was the total energy consumption for each lift station during the last year (as defined by answer in Question 2)?

	Energy Consumption (kWh per month)											
Lift Stations	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Total	____	____	____	____	____	____	____	____	____	____	____	____
or Individual												
L1	____	____	____	____	____	____	____	____	____	____	____	____
L2	____	____	____	____	____	____	____	____	____	____	____	____
L3	____	____	____	____	____	____	____	____	____	____	____	____
L4	____	____	____	____	____	____	____	____	____	____	____	____
L5	____	____	____	____	____	____	____	____	____	____	____	____
L6	____	____	____	____	____	____	____	____	____	____	____	____
L7	____	____	____	____	____	____	____	____	____	____	____	____
L8	____	____	____	____	____	____	____	____	____	____	____	____
L9	____	____	____	____	____	____	____	____	____	____	____	____
L10	____	____	____	____	____	____	____	____	____	____	____	____

Include a list of lift station names and corresponding months.

Appendix C: GMU agreement with Loudoun Water

LOUDOUN WATER

Data Use Agreement

Loudoun Water's Geographic Information Systems (GIS) data and system operational data are being provided to Ali Bakhshi (a Ph.D. Candidate at George Mason University) for the express purpose of facilitating the execution of a Research Project, "A GIS Approach for Carbon Footprint Estimation of Municipal Wastewater and Water Distribution" as part of his doctoral program. These data and any derived products may not be used for any other purpose. All rights to these data expire concurrent with the completion of this Research Project. It is Ali Bakhshi's and George Mason University's responsibility to secure access to these data and all products derived thereby, and to treat said data and products as confidential. These data may not be copied or redistributed without Loudoun Water's express written permission.

Derived products (maps, graphics, reports, models, etc.) may be retained by GMU at the conclusion of this research effort. The original GIS data, and any derived data that retains geometric coordinate information for Loudoun Water's water and wastewater assets, must be deleted. Sensitive information such as the sizes of major water and sewer mains, the locations of pumping facilities and vaults, key operational parameters, and customer locations, shall not be shown on any maps, graphics, or reports that are available to the public. Loudoun Water reserves the right to designate as sensitive any data layer or data element that has been provided.

All results of the Research Project, including maps, reports, raw data, and models, shall be shared with Loudoun Water.

All water and wastewater data are the property of Loudoun Water, and were last updated on April 30, 2009. Base map data and aerial photography are the property of Loudoun County Office of Mapping and Geographic Information (all rights reserved, last updated March 2009). These data and all maps thereby derived are considered best available information and are provided "as-is" without warranties of any kind, expressed or implied, including but not limited to warranties of suitability to a particular purpose or use.

By signature below, you agree to the terms of this Data Use Agreement.

Michael W. Beardslee
Manager of GIS, Engineering Division
Loudoun Water

Ali Bakhshi
Ph.D. Candidate
George Mason University

Sharon deMonsabert, Ph.D.
Professor
George Mason University

Michael Laskofski
Director, Office of Sponsored Programs
George Mason University

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Appendix D: Lower Potomac Energy Calculation

The lift station theoretical power consumption for Long Branch pump house is shown below:

Long Branch Lift Station Theoretical Energy Consumption

Head added by the pump= Static head + Friction loss;
Friction loss= .002083 * Leq*{(gpm **1.85)/(d**4.8655)}
DNINVELV= 48.6 FEET, UPINVELV= 36.75 FEET
Dia= 20 inch
Pipe length L= 2070 feet
Leq= 1.5* pipe length= 3105feet
Pump total capacity: 7.1 MGD
Average daily flow=2.1 MGD (30% of pump cap)
Gpm= MGD*1,000,000/(24*60)= 1458.3
Static head= 48.6-36.75= 11.85 feet
Friction Loss= 24.57 feet
Pump head= 11.85 + 24.57= 36.43 feet
Water HP= Pump head* gpm/3956
Water Hp= 36.43* 1458.3/3956= 13.42
Assume pump efficiency= 0.9 and motor efficiency= 0.95
BHP= WHP/eff= 13.42/0.95= 14.12
KW= 0.7457*BHP/motor eff= 0.7457*14.12/0.9= 11.7
Assume that the pump run time is 22 hrs/day:
KWH= KW * run time-hrs
KWH= 11.7* 22 hrs= 257.4 KWH
Calculated Embodied Energy= 257.4/2.1= 123 KWH/Mgal;

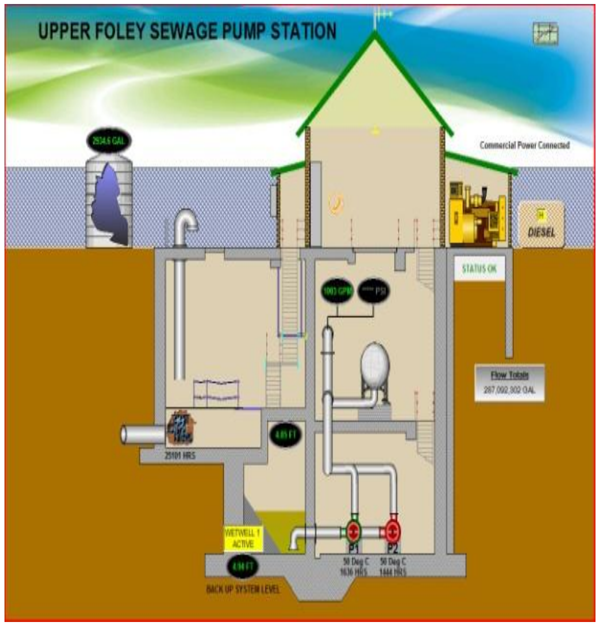
Reported Energy Consumption for Long Branch Lift Station

Long Branch lift station (4 pumps plus building HVAC) = 160,320 KWH/year

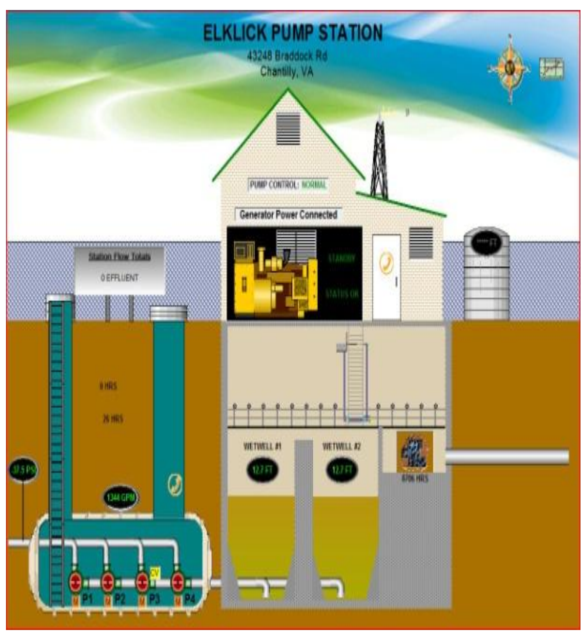
Actual Embodied energy for sewer collection = 160,320 KWH/year/(2.1MGD*365days/year) = 209 KWH/Mgal

Deviation between Actual and Theoretical- Embodied Energy= 41%

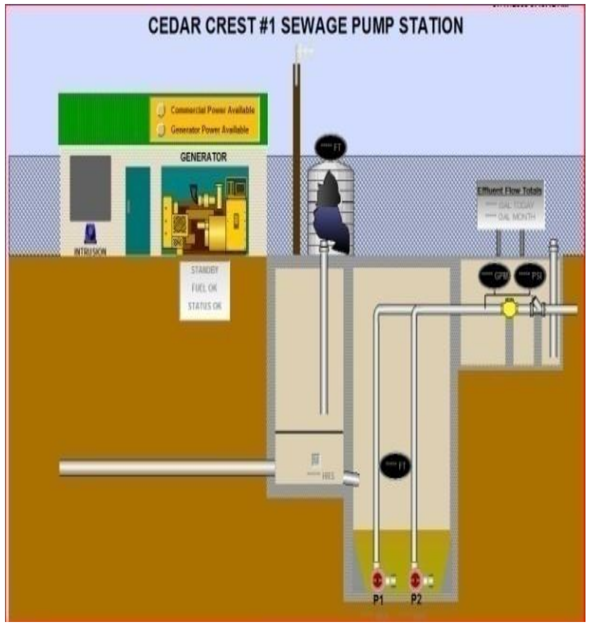
Appendix E: Dulles South Pump Station Configuration



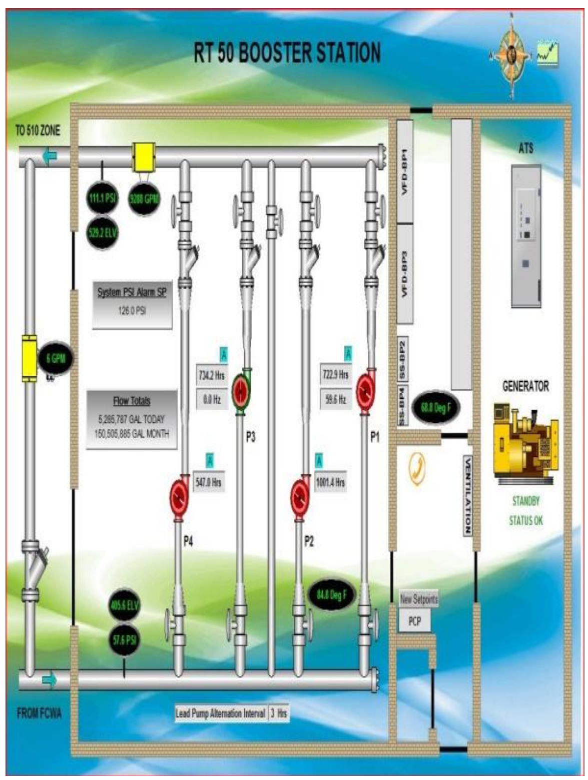
Upper Foley Lift Station



Elklick Lift Station



Cedar Crest #1 Lift Station



Rt 50 Pump Station
Courtesy of Loudoun Water Authority- SCADA output

Appendix F: Customer Embodied Energy Calculation

GIS Output for a Commercial Type Customer inside Dulles South Region

PARAMETER	**DESIGNATION**	**VALUE**	**UNIT**	**NOTES**
Parcel ID	OBJECTID	4671		
Water Distribution Pump Station Name	Wpump	RT50		
Wastewater Collection Pump Station Name	WWpump	Elklick		
Water Treatment Plant Name	WTP	Corbalis		
Wastewater Treatment Plant Name	WWTP	Blue Plains		
Average Potable Water Demand per Parcel	AGPD	17,364.8	Gal/Day	
Customer Demand for a Parcel	CUST_WF	6.34	Mgal/yr	1
Customer Estimated Wastewater Generation	CUST_WWF	5.07	Mgal/yr	2
Embodied Energy for Water Treatment Plant	WTP_EMB	2.31	MWh/Mgal	
Embodied Energy for Water Distribution Pumps	WpumpEMB	0.49	MWh/Mgal	
Embodied Energy for Sewer Lift Stations	WWpumpEMB	1.17	MWh/Mgal	
Embodied Energy for Wastewater Treatment Plant	WWTP_EMB	2.27	MWh/Mgal	
Customer Energy Allocated to Water Treatment Plant	CUST_WTPE	14.64	MWh	3
Customer Energy Allocated to Water Distribution Pumps	CUST_WPE	3.11	MWh	4
Customer Energy Allocated to Sewer Lift Pumps	CUST_WWPE	5.93	MWh	5
Customer Energy Allocated to Wastewater Treatment Plant	CUST_WWTPE	11.51	MWh	6
Customer Energy Allocated to All Water Segments	CUST_TOTE	35.19	MWh/yr	7
Customer Embodied Energy	CUST_EMB	5.55	MWh/Mgal	8
Emission Coefficient for Water Treatment Plant	WTP_EC	0.49	Tons/MWh	
Emission Coefficient for Water Distribution Pumps	WpumpEC	0.49	Tons/MWh	
Emission Coefficient for Sewer Lifts	WWpumpEC	0.49	Tons/MWh	
Emission Coefficient for Wastewater Treatment Plant	WWTP_EC	0.55	Tons/MWh	

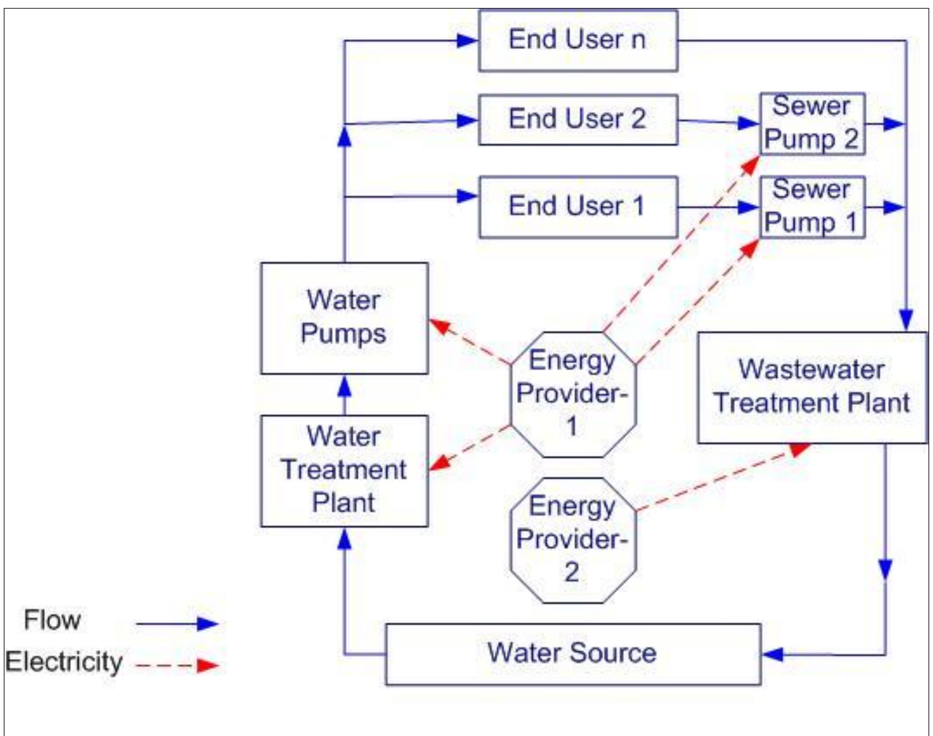
Customer Annual CO2 Emission	CUST_Em	17.93	Tons of CO2/yr	9
Emission Intensity for Water Treatment Plant	WTP_EI	1.13	Tons/Mgal	
Emission Intensity for Water Distribution Pumps	WPUMP_EI	0.24	Tons/Mgal	
Emission Intensity for Sewer Collection Lifts	WWPUMP_EI	0.58	Tons/Mgal	
Emission Intensity for Wastewater treatment Plant	WWTP_EI	1.25	Tons/Mgal	
Customer Emission Intensity for Water Cycle	CUST_EI	3.20	Tons/Mgal	10

Equations for Estimation of Customer Embodied Energy

NOTES	EQUATIONS
1	$\mathrm{CUST_{WF}} = \mathrm{AGPD}\left(17{,}364.8\,\frac{\mathrm{Gallon}}{\mathrm{Day}} \times 336\,\frac{\mathrm{Day}}{\mathrm{Year}}\right) \div 1{,}000{,}000\,\frac{\mathrm{Mgal}}{\mathrm{Gallon}} = 6.34\,\frac{\mathrm{Mgal}}{\mathrm{Year}}$
2	$\mathrm{CUST_{WWF}} = \mathrm{Fraction}\ (0.80) \times \mathrm{CUST_{WF}}\left(6.34\,\frac{\mathrm{Mgal}}{\mathrm{Year}}\right) = 5.07\,\frac{\mathrm{Mgal}}{\mathrm{Year}}$
3	$\mathrm{CUST_{WTPE}} = \mathrm{CUST_{WF}}\left(6.34\,\frac{\mathrm{Mgal}}{\mathrm{Yr}}\right) \times \mathrm{WTP_{EMB}}\left(2.31\,\frac{\mathrm{MWh}}{\mathrm{Mgal}}\right) = 14.64\,\frac{\mathrm{MWh}}{\mathrm{Yr}}$
4	$\mathrm{CUST_{WPE}} = \mathrm{CUST_{WF}}\left(6.34\,\frac{\mathrm{Mgal}}{\mathrm{Yr}}\right) \times \mathrm{WpumpEMB}\left(0.49\,\frac{\mathrm{MWh}}{\mathrm{Mgal}}\right) = 3.11\,\frac{\mathrm{MWh}}{\mathrm{Mgal}}$
5	$\mathrm{CUST_{WWPE}} = \mathrm{CUST_{WWF}}\left(5.07\,\frac{\mathrm{Mgal}}{\mathrm{Yr}}\right) \times \mathrm{WWpumpEMB}\left(1.17\,\frac{\mathrm{MWH}}{\mathrm{Mgal}}\right) = 5.93\,\frac{\mathrm{MWh}}{\mathrm{Yr}}$
6	$\mathrm{CUST_{WWTPE}} = \mathrm{CUST_{WWF}}\left(5.07\,\frac{\mathrm{Mgal}}{\mathrm{Yr}}\right) \times \mathrm{WWTP_{EMB}}\left(2.27\,\frac{\mathrm{MWh}}{\mathrm{Mgal}}\right) = 11.51\,\frac{\mathrm{MWh}}{\mathrm{Yr}}$
7	$\mathrm{CUST_{TOTE}} = \mathrm{CUST_{WTPE}}\left(14.64\,\frac{\mathrm{MWh}}{\mathrm{Yr}}\right) + \mathrm{CUST_{WPE}}\left(3.11\,\frac{\mathrm{MWh}}{\mathrm{Mgal}}\right) + \mathrm{CUST_{WWPE}}\left(5.93\,\frac{\mathrm{MWh}}{\mathrm{Yr}}\right) + \mathrm{CUST_{WWTPE}}\left(11.51\,\frac{\mathrm{MWh}}{\mathrm{Yr}}\right) = 35.19\,\frac{\mathrm{MWh}}{\mathrm{Yr}}$
8	$\mathrm{CUST_{EMB}} = \mathrm{CUST_{TOTE}}\left(35.19\,\frac{\mathrm{MWh}}{\mathrm{Yr}}\right) \div \mathrm{CUST_{WF}}\left(6.34\,\frac{\mathrm{Mgal}}{\mathrm{Year}}\right) = 5.55\,\frac{\mathrm{MWh}}{\mathrm{Mgal}}$
9	$\mathrm{CUST_{Em}} = \mathrm{CUST_{WTPE}}\left(14.64\,\frac{\mathrm{MWh}}{\mathrm{Yr}}\right) \times \mathrm{WTP_{EC}}\left(0.49\,\frac{\mathrm{Tons}}{\mathrm{MWh}}\right) + \mathrm{CUST_{WPE}}\left(3.11\,\frac{\mathrm{MWh}}{\mathrm{Mgal}}\right) \times \mathrm{WpumpEC}\left(0.49\,\frac{\mathrm{Tons}}{\mathrm{MWh}}\right) + \mathrm{CUST_{WWTPE}}\left(11.51\,\frac{\mathrm{MWh}}{\mathrm{Yr}}\right) \times \mathrm{WWTP_{EC}}\left(0.55\,\frac{\mathrm{Tons}}{\mathrm{MWh}}\right) + \mathrm{CUST_{WWPE}}\left(5.93\,\frac{\mathrm{MWh}}{\mathrm{Yr}}\right) \times \mathrm{WWpumpEC}\left(0.49\,\frac{\mathrm{Tons}}{\mathrm{MWh}}\right) = 17.93\,\frac{\mathrm{Tons_{CO2}}}{\mathrm{Yr}}$
10	$\mathrm{CUST_{EI}} = \mathrm{WTP_{EI}}\left(1.13\,\frac{\mathrm{Tons}}{\mathrm{Mgal}}\right) + \mathrm{WPUMP_{EI}}\left(0.24\,\frac{\mathrm{Tons}}{\mathrm{Mgal}}\right) + \mathrm{WWPUMP_{EI}}\left(0.58\,\frac{\mathrm{Tons}}{\mathrm{Mgal}}\right) + \mathrm{WWTP_{EI}}\left(1.25\,\frac{\mathrm{Tons}}{\mathrm{Mgal}}\right) = 3.2\,\frac{\mathrm{TonsCO2}}{\mathrm{Mgal}}$

Appendix G: Model Validation

The following diagram depicts the use of electricity and flow of water in a water system. The total energy input into the water cycle reported by the municipalities must be the same as the sum of all aggregate embodied energy for the end users in this water cycle. A random sample of 61 customers was selected out of a total of 7,299 end users in Dulles South region and the model output energy and the resulting emission were compared with the known input quantities. The validation process and the results are shown below:



Water-Energy Nexus Diagram for Water Cycle

The validation algorithms are presented in the tables using the following equations:

$$\text{Energy Proportion of WTP} = \text{WTP EMB} * \sum \text{WF}_{\text{CUST}}$$
$$\text{Energy Proportion of WWTP} = \text{WWTP EMB} * \sum \text{WWF}_{\text{CUST}}$$
$$\text{Energy Proportion of WPump} = \text{WPump EMB} * \sum \text{WF}_{\text{CUST}}$$
$$\text{Energy Proportion of WWPump} = \text{WWPump EMB} * \sum \text{WWF}_{\text{CUST}}$$

$$\text{Total Energy (GIS output)} = \sum \text{Aggregate energy proportions from WTP, WWTP, WPump, WWPump}$$

$$\begin{aligned}\text{Customer Emission (GIS output)} &= \sum \text{Aggregate emissions from WTP, WWTP, Wpump, WWPump} \\ &= (\text{WF}_{\text{CUST}} * \text{WTP}_{\text{EMB}} * \text{WTP}_{\text{EC}}) + (\text{WF}_{\text{CUST}} * \text{WPump}_{\text{EMB}} * \text{WPump}_{\text{EC}}) \\ &+ (\text{WWF}_{\text{CUST}} * \text{WWPump}_{\text{EMB}} * \text{WWPump}_{\text{EC}}) + (\text{WWF}_{\text{CUST}} * \text{WWTP}_{\text{EMB}} \\ &* \text{WWTP}_{\text{EC}})\end{aligned}$$

Where:

WTP= Water Treatment Plant
WWTP= Wastewater treatment Plant
WPump= Water Distribution Pump
WWPump= Wastewater Lift Station
EMB= Embodied Energy
EC= Emission Coefficient
WF_{CUST} = Customer Water Demand (reported per parcel by water utility)
WWF_{CUST}= Customer Wastewater Flow

Total End Use Flow for sample (water demand for each parcel is reported by the water utility company)	8.40	Mgal
Total End Use Wastewater Flow for sample	6.72	Mgal
Total Wastewater Flow Pumped	4.04	Mgal
Proportion of Energy Used in Water Treatment	19.40	MWh
Proportion of Energy Used in Water Pumping	4.12	MWh
Proportion of Energy Used in Wastewater pumping	6.90	MWh
Proportion of Energy Used in Wastewater Treatment	15.25	MWh
Total calculated Energy from all water segment aggregates	45.67	MWh
Total input energy (measured)	45.67	MWh

Output Energy (calculated) = Input Energy (measured)

Customer (Object ID- 212) GIS Output Emissions = 0.12 Tons/yr; validation follows:
$\text{Emission} = 0.05 + 0.01 + 0.02 + 0.04 = 0.12\ \text{Tons}$

Validation for randomly selected customers is presented in the following tables.

Customer ID	**GIS Result Customer Total Energy (MWh/Yr)**	Customer Water Use (Mgal/Yr)	Customer wastewater Flow treated (Mgal/Yr)	Customer wastewater flow pumped (Mgal/Yr)
OBJECTID	**CUST_TOT_E**	CUST_WF	CUST_WWF	Cust_WWF_pumped
212	**0.24**	0.04	0.04	0.04
213	**0.14**	0.03	0.02	0.02
214	**0.29**	0.05	0.04	0.04
215	**0.33**	0.06	0.05	0.05
216	**0.17**	0.03	0.02	0.02
217	**1.10**	0.20	0.16	0.16
218	**1.36**	0.25	0.20	0.20
219	**1.61**	0.29	0.23	0.23
220	**1.27**	0.23	0.18	0.18
221	**1.23**	0.22	0.18	0.18
222	**1.25**	0.23	0.18	0.18
223	**0.65**	0.12	0.09	0.09
439	**0.25**	0.05	0.04	0.00
440	**1.20**	0.26	0.21	0.00
441	**0.96**	0.21	0.17	0.00
442	**0.63**	0.14	0.11	0.00
443	**0.38**	0.08	0.07	0.00
679	**0.32**	0.07	0.06	0.00
680	**2.09**	0.45	0.36	0.00
681	**0.97**	0.21	0.17	0.00
682	**1.83**	0.40	0.32	0.00
683	**1.19**	0.26	0.21	0.00
684	**0.72**	0.16	0.12	0.00
685	**0.37**	0.08	0.06	0.00
686	**0.98**	0.21	0.17	0.00
687	**0.86**	0.19	0.15	0.00
688	**0.42**	0.09	0.07	0.00
779	**0.34**	0.05	0.04	0.04
780	**1.12**	0.16	0.12	0.12
781	**0.69**	0.10	0.08	0.08
782	**0.77**	0.11	0.09	0.09
783	**0.81**	0.11	0.09	0.09
894	**0.31**	0.06	0.04	0.04
895	**0.21**	0.04	0.03	0.03
896	**0.40**	0.07	0.06	0.06
897	**1.60**	0.29	0.23	0.23
898	**0.22**	0.04	0.03	0.03

Customer ID	**GIS Result Customer Total Energy (MWh/Yr)**	Customer Water Use (Mgal/Yr)	Customer wastewater Flow treated (Mgal/Yr)	Customer wastewater flow pumped (Mgal/Yr)
OBJECTID	**CUST_TOT_E**	CUST_WF	CUST_WWF	Cust_WWF_pumped
1024	**0.48**	0.07	0.05	0.05
1025	**1.19**	0.17	0.13	0.13
1026	**1.34**	0.19	0.15	0.15
1027	**1.67**	0.23	0.19	0.19
1028	**1.12**	0.16	0.12	0.12
224	**1.70**	0.31	0.24	0.24
225	**0.91**	0.16	0.13	0.13
226	**1.53**	0.27	0.22	0.22
227	**0.23**	0.04	0.03	0.03
228	**0.30**	0.05	0.04	0.04
229	**0.98**	0.18	0.14	0.14
230	**0.39**	0.07	0.06	0.06
231	**1.10**	0.20	0.16	0.16
232	**0.34**	0.06	0.05	0.05
233	**0.80**	0.14	0.12	0.12
234	**0.34**	0.07	0.06	0.00
235	**0.19**	0.04	0.03	0.00
236	**0.16**	0.03	0.03	0.00
237	**0.26**	0.06	0.05	0.00
238	**0.30**	0.06	0.05	0.00
239	**0.28**	0.06	0.05	0.00
240	**0.35**	0.08	0.06	0.00
241	**0.19**	0.04	0.03	0.00
242	**0.25**	0.05	0.04	0.00

Customer ID	SubTotal Customer wastewater flow pumped (Mgal/Yr)	Wastewater Pump Embodied Energy (MWh/Mgal)	Water Treatment Plant Embodied Energy (MWh/Mgal)	Water Pump Embodied Energy (MWh/Mgal)
OBJECTID	Cust_WWF_pumped	WWpumpEMB	WTP_EMB	WpumpEMB
212		1.17	2.31	0.49
213		1.17	2.31	0.49
214		1.17	2.31	0.49
215		1.17	2.31	0.49
216		1.17	2.31	0.49
217		1.17	2.31	0.49
218		1.17	2.31	0.49
219		1.17	2.31	0.49
220		1.17	2.31	0.49
221		1.17	2.31	0.49
222		1.17	2.31	0.49
223	1.39	1.17	2.31	0.49
439		0.00	2.31	0.49
440		0.00	2.31	0.49
441		0.00	2.31	0.49
442		0.00	2.31	0.49
443		0.00	2.31	0.49
679		0.00	2.31	0.49
680		0.00	2.31	0.49
681		0.00	2.31	0.49
682		0.00	2.31	0.49
683		0.00	2.31	0.49
684		0.00	2.31	0.49
685		0.00	2.31	0.49
686		0.00	2.31	0.49
687		0.00	2.31	0.49
688		0.00	2.31	0.49
779		3.23	2.31	0.49
780		3.23	2.31	0.49
781		3.23	2.31	0.49
782		3.23	2.31	0.49
783	0.41	3.23	2.31	0.49
894		1.17	2.31	0.49
895		1.17	2.31	0.49
896		1.17	2.31	0.49
897		1.17	2.31	0.49
898	0.39	1.17	2.31	0.49

Customer ID	SubTotal Customer wastewater flow pumped (Mgal/Yr)	Wastewater Pump Embodied Energy (MWh/Mgal)	Water Treatment Plant Embodied Energy (MWh/Mgal)	Water Pump Embodied Energy (MWh/Mgal)
OBJECTID	Cust_WWF_pumped	WWpumpEMB	WTP_EMB	WpumpEMB
1024		3.23	2.31	0.49
1025		3.23	2.31	0.49
1026		3.23	2.31	0.49
1027		3.23	2.31	0.49
1028	0.65	3.23	2.31	0.49
224		1.17	2.31	0.49
225		1.17	2.31	0.49
226		1.17	2.31	0.49
227		1.17	2.31	0.49
228		1.17	2.31	0.49
229		1.17	2.31	0.49
230		1.17	2.31	0.49
231		1.17	2.31	0.49
232		1.17	2.31	0.49
233	1.19	1.17	2.31	0.49
234		0.00	2.31	0.49
235		0.00	2.31	0.49
236		0.00	2.31	0.49
237		0.00	2.31	0.49
238		0.00	2.31	0.49
239		0.00	2.31	0.49
240		0.00	2.31	0.49
241		0.00	2.31	0.49
242		0.00	2.31	0.49

Customer ID	Wastewater Treatment Plant Embodied Energy (MWh/Mgal)	Customer Energy Attributed to water Distribution and Treatment (MWh) [CustFlow * (WTP_EMB+ WpumpEMB)]	Customer Energy Attributed to wastewater Collection Pump and wastewater Treatment (MWh) [CustWWFlow*(WWTP_EMB + WWPump_EMB)]
OBJECTID	WWTP_EMB		
212	2.27	0.12	0.12
213	2.27	0.07	0.07
214	2.27	0.15	0.14
215	2.27	0.16	0.16
216	2.27	0.09	0.08
217	2.27	0.56	0.55
218	2.27	0.69	0.67
219	2.27	0.81	0.80
220	2.27	0.64	0.63
221	2.27	0.62	0.61
222	2.27	0.63	0.62
223	2.27	0.33	0.32
439	2.27	0.15	0.10
440	2.27	0.73	0.47
441	2.27	0.58	0.38
442	2.27	0.38	0.25
443	2.27	0.23	0.15
679	2.27	0.20	0.13
680	2.27	1.27	0.82
681	2.27	0.59	0.38
682	2.27	1.11	0.72
683	2.27	0.72	0.47
684	2.27	0.44	0.28
685	2.27	0.22	0.15
686	2.27	0.60	0.39
687	2.27	0.52	0.34
688	2.27	0.25	0.16
779	2.27	0.13	0.21
780	2.27	0.44	0.69
781	2.27	0.27	0.42
782	2.27	0.30	0.47
783	2.27	0.32	0.50
894	2.27	0.15	0.15
895	2.27	0.10	0.10
896	2.27	0.20	0.20
897	2.27	0.81	0.79
898	2.27	0.11	0.11

Customer ID	Wastewater Treatment Plant Embodied Energy (MWh/Mgal)	Customer Energy Attributed to water Distribution and Treatment (MWh) [CustFlow * (WTP_EMB+ WpumpEMB)]	Customer Energy Attributed to wastewater Collection Pump and wastewater Treatment (MWh) [CustWWFlow*(WWTP_EMB + WWPump_EMB)]
OBJECTID	WWTP_EMB		
1024	2.27	0.19	0.29
1025	2.27	0.46	0.73
1026	2.27	0.52	0.82
1027	2.27	0.65	1.02
1028	2.27	0.44	0.69
224	2.27	0.86	0.84
225	2.27	0.46	0.45
226	2.27	0.77	0.76
227	2.27	0.12	0.11
228	2.27	0.15	0.15
229	2.27	0.50	0.49
230	2.27	0.20	0.19
231	2.27	0.55	0.54
232	2.27	0.17	0.17
233	2.27	0.40	0.40
234	2.27	0.21	0.13
235	2.27	0.12	0.08
236	2.27	0.10	0.06
237	2.27	0.16	0.10
238	2.27	0.18	0.12
239	2.27	0.17	0.11
240	2.27	0.21	0.14
241	2.27	0.12	0.08
242	2.27	0.15	0.10

Customer ID	**Validated Customer Energy Total (MWh/Yr) Sum**	Emission coefficient for WTP	Emission coefficient for Pump	Emission coefficient for Sewer pump	Emission coefficient for WWTP
OBJECTID	**MWh/Yr**	WTP_EC	WpumpEC	WWpumpEC	WWTP_EC
212	**0.24**	0.49	0.49	0.49	0.55
213	**0.14**	0.49	0.49	0.49	0.55
214	**0.29**	0.49	0.49	0.49	0.55
215	**0.33**	0.49	0.49	0.49	0.55
216	**0.17**	0.49	0.49	0.49	0.55
217	**1.10**	0.49	0.49	0.49	0.55
218	**1.36**	0.49	0.49	0.49	0.55
219	**1.61**	0.49	0.49	0.49	0.55
220	**1.27**	0.49	0.49	0.49	0.55
221	**1.23**	0.49	0.49	0.49	0.55
222	**1.25**	0.49	0.49	0.49	0.55
223	**0.65**	0.49	0.49	0.49	0.55
439	**0.25**	0.49	0.49	0.00	0.55
440	**1.20**	0.49	0.49	0.00	0.55
441	**0.96**	0.49	0.49	0.00	0.55
442	**0.63**	0.49	0.49	0.00	0.55
443	**0.38**	0.49	0.49	0.00	0.55
679	**0.32**	0.49	0.49	0.00	0.55
680	**2.09**	0.49	0.49	0.00	0.55
681	**0.97**	0.49	0.49	0.00	0.55
682	**1.83**	0.49	0.49	0.00	0.55
683	**1.19**	0.49	0.49	0.00	0.55
684	**0.72**	0.49	0.49	0.00	0.55
685	**0.37**	0.49	0.49	0.00	0.55
686	**0.98**	0.49	0.49	0.00	0.55
687	**0.86**	0.49	0.49	0.00	0.55
688	**0.42**	0.49	0.49	0.00	0.55
779	**0.34**	0.49	0.49	0.49	0.55
780	**1.12**	0.49	0.49	0.49	0.55
781	**0.69**	0.49	0.49	0.49	0.55
782	**0.77**	0.49	0.49	0.49	0.55
783	**0.81**	0.49	0.49	0.49	0.55
894	**0.31**	0.49	0.49	0.49	0.55
895	**0.21**	0.49	0.49	0.49	0.55
896	**0.40**	0.49	0.49	0.49	0.55
897	**1.60**	0.49	0.49	0.49	0.55
898	**0.22**	0.49	0.49	0.49	0.55

Customer ID	**Validated Customer Energy Total (MWh/Yr) Sum**	Emission coefficient for WTP	Emission coefficient for Pump	Emission coefficient for Sewer pump	Emission coefficient for WWTP
OBJECTID	**MWh/Yr**	WTP_EC	WpumpEC	WWpumpEC	WWTP_EC
1024	**0.48**	0.49	0.49	0.49	0.55
1025	**1.19**	0.49	0.49	0.49	0.55
1026	**1.34**	0.49	0.49	0.49	0.55
1027	**1.67**	0.49	0.49	0.49	0.55
1028	**1.12**	0.49	0.49	0.49	0.55
224	**1.70**	0.49	0.49	0.49	0.55
225	**0.91**	0.49	0.49	0.49	0.55
226	**1.53**	0.49	0.49	0.49	0.55
227	**0.23**	0.49	0.49	0.49	0.55
228	**0.30**	0.49	0.49	0.49	0.55
229	**0.98**	0.49	0.49	0.49	0.55
230	**0.39**	0.49	0.49	0.49	0.55
231	**1.10**	0.49	0.49	0.49	0.55
232	**0.34**	0.49	0.49	0.49	0.55
233	**0.80**	0.49	0.49	0.49	0.55
234	**0.34**	0.49	0.49	0.00	0.55
235	**0.19**	0.49	0.49	0.00	0.55
236	**0.16**	0.49	0.49	0.00	0.55
237	**0.26**	0.49	0.49	0.00	0.55
238	**0.30**	0.49	0.49	0.00	0.55
239	**0.28**	0.49	0.49	0.00	0.55
240	**0.35**	0.49	0.49	0.00	0.55
241	**0.19**	0.49	0.49	0.00	0.55
242	**0.25**	0.49	0.49	0.00	0.55

Customer ID	Customer emission for WTP WF*WTP_EMB*WTP_EC	Customer emission for Wpump WF*Wpump_EMB*Wpump_EC	Customer emission for Wwpump WWF*WWPump_EMB*Wwpump_EC
OBJECTID	Tons	Tons	Tons
212	0.05	0.01	0.02
213	0.03	0.01	0.01
214	0.06	0.01	0.02
215	0.07	0.01	0.03
216	0.03	0.01	0.01
217	0.22	0.05	0.09
218	0.28	0.06	0.11
219	0.33	0.07	0.13
220	0.26	0.05	0.10
221	0.25	0.05	0.10
222	0.25	0.05	0.10
223	0.13	0.03	0.05
439	0.06	0.01	0.00
440	0.29	0.06	0.00
441	0.24	0.05	0.00
442	0.15	0.03	0.00
443	0.09	0.02	0.00
679	0.08	0.02	0.00
680	0.51	0.11	0.00
681	0.24	0.05	0.00
682	0.45	0.10	0.00
683	0.29	0.06	0.00
684	0.18	0.04	0.00
685	0.09	0.02	0.00
686	0.24	0.05	0.00
687	0.21	0.04	0.00
688	0.10	0.02	0.00
779	0.05	0.01	0.06
780	0.18	0.04	0.20
781	0.11	0.02	0.12
782	0.12	0.03	0.14
783	0.13	0.03	0.14
894	0.06	0.01	0.03
895	0.04	0.01	0.02
896	0.08	0.02	0.03
897	0.33	0.07	0.13
898	0.04	0.01	0.02

Customer ID	Customer emission for WTP WF*WTP_EMB*WTP_EC	Customer emission for Wpump WF*Wpump_EMB*Wpump_EC	Customer emission for Wwpump WWF*WWPump_EMB*Wwpump_EC
OBJECTID	Tons	Tons	Tons
1024	0.08	0.02	0.08
1025	0.19	0.04	0.21
1026	0.21	0.04	0.24
1027	0.26	0.06	0.29
1028	0.18	0.04	0.20
224	0.35	0.07	0.14
225	0.18	0.04	0.07
226	0.31	0.07	0.13
227	0.05	0.01	0.02
228	0.06	0.01	0.02
229	0.20	0.04	0.08
230	0.08	0.02	0.03
231	0.22	0.05	0.09
232	0.07	0.01	0.03
233	0.16	0.03	0.07
234	0.08	0.02	0.00
235	0.05	0.01	0.00
236	0.04	0.01	0.00
237	0.06	0.01	0.00
238	0.07	0.02	0.00
239	0.07	0.01	0.00
240	0.09	0.02	0.00
241	0.05	0.01	0.00
242	0.06	0.01	0.00

Customer ID	Customer emission for WWTP WWF*WWTP_EMB*WWTP_EC	**Validated Total Em**	Customer Annual Emission (Ton CO2/Yr)
OBJECTID	Tons	**Tons**	CUST_Em
212	0.04	**0.12**	0.12
213	0.03	**0.07**	0.07
214	0.05	**0.15**	0.15
215	0.06	**0.17**	0.17
216	0.03	**0.09**	0.09
217	0.20	**0.56**	0.56
218	0.24	**0.69**	0.69
219	0.29	**0.82**	0.82
220	0.23	**0.65**	0.65
221	0.22	**0.63**	0.63
222	0.22	**0.64**	0.64
223	0.12	**0.33**	0.33
439	0.05	**0.13**	0.13
440	0.26	**0.62**	0.62
441	0.21	**0.50**	0.50
442	0.14	**0.32**	0.32
443	0.08	**0.20**	0.20
679	0.07	**0.17**	0.17
680	0.45	**1.07**	1.07
681	0.21	**0.50**	0.50
682	0.40	**0.94**	0.94
683	0.26	**0.61**	0.61
684	0.16	**0.37**	0.37
685	0.08	**0.19**	0.19
686	0.21	**0.51**	0.51
687	0.19	**0.44**	0.44
688	0.09	**0.21**	0.21
779	0.05	**0.17**	0.17
780	0.16	**0.57**	0.57
781	0.10	**0.35**	0.35
782	0.11	**0.39**	0.39
783	0.11	**0.41**	0.41
894	0.06	**0.16**	0.16
895	0.04	**0.11**	0.11
896	0.07	**0.20**	0.20
897	0.29	**0.82**	0.82
898	0.04	**0.11**	0.11

Customer ID	Customer emission for WWTP WWF*WWTP_EMB*WWTP_EC	**Validated Total Em**	Customer Annual Emission (Ton CO2/Yr)
OBJECTID	Tons	**Tons**	CUST_Em
1024	0.07	**0.24**	0.24
1025	0.17	**0.60**	0.60
1026	0.19	**0.68**	0.68
1027	0.23	**0.84**	0.84
1028	0.16	**0.57**	0.57
224	0.31	**0.87**	0.87
225	0.16	**0.46**	0.46
226	0.27	**0.78**	0.78
227	0.04	**0.12**	0.12
228	0.05	**0.15**	0.15
229	0.18	**0.50**	0.50
230	0.07	**0.20**	0.20
231	0.20	**0.56**	0.56
232	0.06	**0.17**	0.17
233	0.14	**0.41**	0.41
234	0.07	**0.17**	0.17
235	0.04	**0.10**	0.10
236	0.03	**0.08**	0.08
237	0.06	**0.13**	0.13
238	0.06	**0.15**	0.15
239	0.06	**0.14**	0.14
240	0.08	**0.18**	0.18
241	0.04	**0.10**	0.10
242	0.05	**0.13**	0.13

The model input parameter namely Brambelton water pump embodied energy can also be validated. One can estimate the embodied energy of water pumps using the hydraulic formulas. The following shows the procedure and identifies the known values:

- Region's highest end user elevations to serve (380 feet -403 feet)
- Region's total water demand (1,396 Mgal/Yr, or 2,656 gpm)
- Adjacent pressure zone (510 feet) serving end user elevations up to 380 ft
- Minimum acceptable operating pressure in distribution pipes (80 psi)

The minimum Hydraulic Grade Line (HGL) for the Brambelton must be determined in order to serve a customer located at 395 feet elevation (Eq. 6):

$$\text{HGL} > \textit{Highest Elevation} + 2.31 \times \textit{Minimum Pressure}$$

$$\text{Highest Elevation} = 395\ \text{ft} + 2.31\frac{\text{ft}}{\text{psi}} \times 80\ \text{psi} = 580\ \text{ft}$$

$$\text{Total Dynamic Head} = \text{Differnce in HGLs between two regions in water supply}$$

$$= 580\ \text{ft} - 510\ \text{ft} = 70\ \text{ft}$$

Equations 1 and 4 can be applied to calculate the power to move water against this head (Total Dynamic Head- TDH), with a reasonable assumption for the pump and motor efficiencies:

$$\text{Pump Power} = \text{gpm} \times \text{TDH} \times \frac{0.746}{3{,}960 \times 0.85 \times 0.90} = 2{,}656 \times 70 \times \frac{0.746}{3{,}960 \times 0.85 \times 0.90}$$

$$= 45.78\ \text{KW}$$

A pump run-time of 24 hours per day is considered; total energy of the pumping water can be calculated:

$$\text{Pump Energy} = 45.78\ \text{KW} \times 24\,\frac{\text{hrs}}{\text{day}} \times \frac{365\text{days}}{\text{Yr}} \times \frac{1\text{KW}}{1000\text{W}} = 401\ \text{MWh}$$

The Brambelton theoretical pump embodied energy based on one end user elevation is:

$$\text{Water Pump Embodied Energy} = \frac{401\ \text{MWh}}{1{,}396\ \text{Mgal}} = 0.287\,\frac{\text{MWh}}{\text{Mgal}}$$

The derived value for a set of end user can be determined and the mean value may be used to predict the Brambelton water distribution pump embodied energy in the absence of the actual reported value (0.28 MWh/Mgal).

The above algorithm is performed for end users that have elevation above the highest elevation in the adjacent pressure zone. The mean embodied energy, as determined by the hydraulic calculation (0.27 MWh/Mgal) may be applied for use in the model. The following table shows the calculated values for each end user based on above procedure..

Water Pump Embodied Energy Prediction							
Brambelton OBJECTID	Par_Elev- ft Brambelton	Oper pressure- psi	HGL- Service Elevation- ft	HGL-Adj Pressure Zone -ft	Diff in HGL(TDH)- ft	Area Water Demand- gpm	Conversion Factor
1.00	403.07	80	587.067	510	77.067	2656	0.000246253
2.00	402.92	80	586.919	510	76.919	2656	0.000246253
3.00	402.44	80	586.442	510	76.442	2656	0.000246253
4.00	401.63	80	585.634	510	75.634	2656	0.000246253
5.00	401.47	80	585.47	510	75.47	2656	0.000246253
6.00	399.72	80	583.723	510	73.723	2656	0.000246253
7.00	399.16	80	583.155	510	73.155	2656	0.000246253
8.00	397.06	80	581.059	510	71.059	2656	0.000246253
9.00	396.61	80	580.612	510	70.612	2656	0.000246253
10.00	395.45	80	579.448	510	69.448	2656	0.000246253
11.00	394.76	80	578.757	510	68.757	2656	0.000246253
12.00	394.46	80	578.457	510	68.457	2656	0.000246253
13.00	394.33	80	578.334	510	68.334	2656	0.000246253
14.00	393.95	80	577.953	510	67.953	2656	0.000246253
15.00	393.49	80	577.485	510	67.485	2656	0.000246253
16.00	392.29	80	576.287	510	66.287	2656	0.000246253
17.00	391.94	80	575.944	510	65.944	2656	0.000246253
18.00	390.43	80	574.431	510	64.431	2656	0.000246253
19.00	389.61	80	573.614	510	63.614	2656	0.000246253
20.00	388.64	80	572.637	510	62.637	2656	0.000246253
21.00	388.61	80	572.613	510	62.613	2656	0.000246253
22.00	388.61	80	572.612	510	62.612	2656	0.000246253
23.00	386.26	80	570.259	510	60.259	2656	0.000246253
24.00	385.04	80	569.04	510	59.04	2656	0.000246253
25.00	382.82	80	566.816	510	56.816	2656	0.000246253
26.00	382.49	80	566.49	510	56.49	2656	0.000246253
27.00	382.32	80	566.316	510	56.316	2656	0.000246253
28.00	381.79	80	565.791	510	55.791	2656	0.000246253
29.00	381.45	80	565.447	510	55.447	2656	0.000246253
30.00	380.12	80	564.12	510	54.12	2656	0.000246253

Water Pump Embodied Energy Prediction						
Brambelton OBJECTID	Pump Power- KW	Pump Run-Time-hrs/day	Days/yr	MWh	Annual Demand-Mgal	EMB-MWh/Mgal
1.00	50.40559	24	365	441.553	1396	0.32
2.00	50.30879	24	365	440.705	1396	0.32
3.00	49.99681	24	365	437.9721	1396	0.31
4.00	49.46834	24	365	433.3427	1396	0.31
5.00	49.36108	24	365	432.403	1396	0.31
6.00	48.21845	24	365	422.3937	1396	0.30
7.00	47.84695	24	365	419.1393	1396	0.30
8.00	46.47607	24	365	407.1303	1396	0.29
9.00	46.18371	24	365	404.5693	1396	0.29
10.00	45.42239	24	365	397.9002	1396	0.29
11.00	44.97045	24	365	393.9411	1396	0.28
12.00	44.77423	24	365	392.2223	1396	0.28
13.00	44.69378	24	365	391.5175	1396	0.28
14.00	44.44459	24	365	389.3346	1396	0.28
15.00	44.1385	24	365	386.6532	1396	0.28
16.00	43.35495	24	365	379.7893	1396	0.27
17.00	43.13061	24	365	377.8241	1396	0.27
18.00	42.14103	24	365	369.1554	1396	0.26
19.00	41.60667	24	365	364.4744	1396	0.26
20.00	40.96767	24	365	358.8768	1396	0.26
21.00	40.95197	24	365	358.7393	1396	0.26
22.00	40.95132	24	365	358.7335	1396	0.26
23.00	39.41234	24	365	345.2521	1396	0.25
24.00	38.61505	24	365	338.2679	1396	0.24
25.00	37.16045	24	365	325.5255	1396	0.23
26.00	36.94723	24	365	323.6577	1396	0.23
27.00	36.83342	24	365	322.6608	1396	0.23
28.00	36.49005	24	365	319.6528	1396	0.23
29.00	36.26505	24	365	317.6819	1396	0.23
30.00	35.39713	24	365	310.0789	1396	0.22
	Water Pump Predicted EMB (MWh/Mgal) (Average)					0.27

Appendix H: Sample of GIS Output

Customer ID	Customer Type and Water Use		Parcel Size (Acre)	Customer Water Use (Mgal/Yr)	Customer wastewater Flow (Mgal/Yr)
OBJECTID	CnType	AGPD (Gal/day)	PA_Acre	CUST_WF	CUST_WWF
212.00	RE	120.48	0.06	0.04	0.04
213.00	RE	69.44	0.04	0.03	0.02
214.00	RE	143.77	0.04	0.05	0.04
215.00	RE	160.49	0.06	0.06	0.05
216.00	RE	83.19	0.04	0.03	0.02
217.00	RE	544.40	0.46	0.20	0.16
218.00	RE	671.92	0.46	0.25	0.20
219.00	RE	795.88	0.46	0.29	0.23
220.00	RE	625.71	0.46	0.23	0.18
221.00	RE	605.34	0.46	0.22	0.18
222.00	RE	616.93	0.46	0.23	0.18
223.00	RE	319.72	0.46	0.12	0.09
439.00	RE	146.84	0.60	0.05	0.04
440.00	RE	712.43	0.58	0.26	0.21
441.00	RE	572.09	0.50	0.21	0.17
442.00	RE	371.62	0.56	0.14	0.11
443.00	RE	227.26	0.53	0.08	0.07
679.00	RE	191.15	0.54	0.07	0.06
680.00	RE	1238.59	0.49	0.45	0.36
681.00	RE	575.13	0.60	0.21	0.17
682.00	RE	1089.05	0.47	0.40	0.32
683.00	RE	703.46	0.75	0.26	0.21
684.00	RE	426.22	0.72	0.16	0.12
685.00	RE	219.41	0.52	0.08	0.06
686.00	RE	584.34	0.56	0.21	0.17
687.00	RE	508.96	0.48	0.19	0.15
688.00	RE	247.81	0.56	0.09	0.07
779.00	RE	128.34	0.25	0.05	0.04
780.00	RE	427.75	0.23	0.16	0.12
781.00	RE	262.20	0.20	0.10	0.08
782.00	RE	293.34	0.26	0.11	0.09
783.00	RE	308.25	0.28	0.11	0.09

Customer ID	Customer Energy Use attributed to all water cycle segments (Mwh/Yr)			
OBJECTID	CUST_WTPE	CUST_WPE	CUST_WWPE	CUST_WWTPE
212.00	0.10	0.02	0.04	0.08
213.00	0.06	0.01	0.02	0.05
214.00	0.12	0.03	0.05	0.10
215.00	0.14	0.03	0.05	0.11
216.00	0.07	0.01	0.03	0.06
217.00	0.46	0.10	0.19	0.36
218.00	0.57	0.12	0.23	0.45
219.00	0.67	0.14	0.27	0.53
220.00	0.53	0.11	0.21	0.41
221.00	0.51	0.11	0.21	0.40
222.00	0.52	0.11	0.21	0.41
223.00	0.27	0.06	0.11	0.21
439.00	0.12	0.03	0.00	0.10
440.00	0.60	0.13	0.00	0.47
441.00	0.48	0.10	0.00	0.38
442.00	0.31	0.07	0.00	0.25
443.00	0.19	0.04	0.00	0.15
679.00	0.16	0.03	0.00	0.13
680.00	1.04	0.22	0.00	0.82
681.00	0.48	0.10	0.00	0.38
682.00	0.92	0.19	0.00	0.72
683.00	0.59	0.13	0.00	0.47
684.00	0.36	0.08	0.00	0.28
685.00	0.18	0.04	0.00	0.15
686.00	0.49	0.10	0.00	0.39
687.00	0.43	0.09	0.00	0.34
688.00	0.21	0.04	0.00	0.16
779.00	0.11	0.02	0.12	0.09
780.00	0.36	0.08	0.40	0.28
781.00	0.22	0.05	0.25	0.17
782.00	0.25	0.05	0.28	0.19
783.00	0.26	0.06	0.29	0.20

Customer ID	Wastewater Lift Station Name, Flow (Mgal/Yr), Energy (MWh/Yr) , Embodied Energy (MWh/Mgal), Emission Intensity (Ton CO2/Mgal), Emission (Tons CO2/Yr), and Power Supplier Emission Coefficient (Tons CO2/MWh)						
OBJECTID	StationN_2	WWpumpF_1	WWpumpE	WWpumpEMB	WWpumpEC	WWpumpEI	WWpumpEm
212.00	Elklick WWPS	441.60	518.78	1.17	0.49	0.58	254.20
213.00	Elklick WWPS	441.60	518.78	1.17	0.49	0.58	254.20
214.00	Elklick WWPS	441.60	518.78	1.17	0.49	0.58	254.20
215.00	Elklick WWPS	441.60	518.78	1.17	0.49	0.58	254.20
216.00	Elklick WWPS	441.60	518.78	1.17	0.49	0.58	254.20
217.00	Elklick WWPS	441.60	518.78	1.17	0.49	0.58	254.20
218.00	Elklick WWPS	441.60	518.78	1.17	0.49	0.58	254.20
219.00	Elklick WWPS	441.60	518.78	1.17	0.49	0.58	254.20
220.00	Elklick WWPS	441.60	518.78	1.17	0.49	0.58	254.20
221.00	Elklick WWPS	441.60	518.78	1.17	0.49	0.58	254.20
222.00	Elklick WWPS	441.60	518.78	1.17	0.49	0.58	254.20
223.00	Elklick WWPS	441.60	518.78	1.17	0.49	0.58	254.20
439.00		0.00	0.00	0.00	0.00	0.00	0.00
440.00		0.00	0.00	0.00	0.00	0.00	0.00
441.00		0.00	0.00	0.00	0.00	0.00	0.00
442.00		0.00	0.00	0.00	0.00	0.00	0.00
443.00		0.00	0.00	0.00	0.00	0.00	0.00
679.00		0.00	0.00	0.00	0.00	0.00	0.00
680.00		0.00	0.00	0.00	0.00	0.00	0.00
681.00		0.00	0.00	0.00	0.00	0.00	0.00
682.00		0.00	0.00	0.00	0.00	0.00	0.00
683.00		0.00	0.00	0.00	0.00	0.00	0.00
684.00		0.00	0.00	0.00	0.00	0.00	0.00
685.00		0.00	0.00	0.00	0.00	0.00	0.00
686.00		0.00	0.00	0.00	0.00	0.00	0.00
687.00		0.00	0.00	0.00	0.00	0.00	0.00
688.00		0.00	0.00	0.00	0.00	0.00	0.00
779.00	Upper Foley WW	105.82	208.00	3.23	0.49	1.58	87.03
780.00	Upper Foley WW	105.82	208.00	3.23	0.49	1.58	87.03
781.00	Upper Foley WW	105.82	208.00	3.23	0.49	1.58	87.03
782.00	Upper Foley WW	105.82	208.00	3.23	0.49	1.58	87.03
783.00	Upper Foley WW	105.82	208.00	3.23	0.49	1.58	87.03

Customer ID	Wastewater Treatment Plant Name, Flow (Mgal/Yr), Energy (MWh/Yr) , Embodied Energy (MWh/Mgal), Emission Intensity (Ton CO2/Mgal), Emission (Tons CO2/Yr), and Power Supplier Emission Coefficient (Tons CO2/MWh)							Parcel Elevation (ft)
OBJECTID	PlantName_	WWTP_F	WWTP_E	WWTP_EMB	WWTP_Em	WWTP_EC	WWTP_EI	ParMeanEl
212.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	293.97
213.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	297.10
214.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	296.97
215.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	296.87
216.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	296.53
217.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	322.20
218.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	318.94
219.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	318.47
220.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	319.31
221.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	321.82
222.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	318.57
223.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	314.90
439.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	326.57
440.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	334.71
441.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	322.19
442.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	327.84
443.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	332.85
679.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	345.70
680.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	341.07
681.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	343.99
682.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	340.62
683.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	342.32
684.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	339.62
685.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	337.49
686.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	340.00
687.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	338.52
688.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	338.48
779.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	352.25
780.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	350.38
781.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	349.20
782.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	351.34
783.00	Blue Plain	116496.37	264550.31	2.27	145502.67	0.55	1.25	352.09

Customer ID	Customer Total Energy (MWh/Yr)	Customer Emission Intensity (Tons CO2/Mgal)	Customer Embodied Energy (MWh/Mgal)	Customer Annual Emission (Ton CO2/Yr)	Water Flow (Mgal/Yr)	Lift Station Pump flow (Mgal/Yr)
OBJECTID	CUST_TOT_E	CUST_EI	CUST_EMB	CUST_Em	Tot_WF	WWpumpF
212.00	0.24	3.20	5.55	0.12	481.16	441.60
213.00	0.14	3.20	5.55	0.07	481.16	441.60
214.00	0.29	3.20	5.55	0.15	481.16	441.60
215.00	0.33	3.20	5.55	0.17	481.16	441.60
216.00	0.17	3.20	5.55	0.09	481.16	441.60
217.00	1.10	3.20	5.55	0.56	481.16	441.60
218.00	1.36	3.20	5.55	0.69	481.16	441.60
219.00	1.61	3.20	5.55	0.82	481.16	441.60
220.00	1.27	3.20	5.55	0.65	481.16	441.60
221.00	1.23	3.20	5.55	0.63	481.16	441.60
222.00	1.25	3.20	5.55	0.64	481.16	441.60
223.00	0.65	3.20	5.55	0.33	481.16	441.60
439.00	0.25	2.62	4.62	0.13	0.00	0.00
440.00	1.20	2.62	4.62	0.62	0.00	0.00
441.00	0.96	2.62	4.62	0.50	0.00	0.00
442.00	0.63	2.62	4.62	0.32	0.00	0.00
443.00	0.38	2.62	4.62	0.20	0.00	0.00
679.00	0.32	2.62	4.62	0.17	0.00	0.00
680.00	2.09	2.62	4.62	1.07	0.00	0.00
681.00	0.97	2.62	4.62	0.50	0.00	0.00
682.00	1.83	2.62	4.62	0.94	0.00	0.00
683.00	1.19	2.62	4.62	0.61	0.00	0.00
684.00	0.72	2.62	4.62	0.37	0.00	0.00
685.00	0.37	2.62	4.62	0.19	0.00	0.00
686.00	0.98	2.62	4.62	0.51	0.00	0.00
687.00	0.86	2.62	4.62	0.44	0.00	0.00
688.00	0.42	2.62	4.62	0.21	0.00	0.00
779.00	0.34	4.20	7.20	0.17	68.11	55.00
780.00	1.12	4.20	7.20	0.57	68.11	55.00
781.00	0.69	4.20	7.20	0.35	68.11	55.00
782.00	0.77	4.20	7.20	0.39	68.11	55.00
783.00	0.81	4.20	7.20	0.41	68.11	55.00

Customer ID	Water Treatment Plant Name, Flow (Mgal/Yr), Energy (MWh/Yr) , Embodied Energy (MWh/Mgal), Emission Intensity (Ton CO2/Mgal), Emission (Tons CO2/Yr), and Power Supplier Emission Coefficient (Tons CO2/MWh)						
OBJECTID	PlantName	WTP_Flow	WTP_E	WTP_EMB	WTP_EC	WTP_EI	WTP_Em
212.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
213.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
214.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
215.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
216.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
217.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
218.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
219.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
220.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
221.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
222.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
223.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
439.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
440.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
441.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
442.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
443.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
679.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
680.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
681.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
682.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
683.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
684.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
685.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
686.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
687.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
688.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
779.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
780.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
781.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
782.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62
783.00	Corbalis	31058.00	71613.50	2.31	0.49	1.13	35090.62

Customer ID	Water Distribution Pump Name, Flow (Mgal/Yr), Energy (MWh/Yr) , Embodied Energy (MWh/Mgal), Emission Intensity (Ton CO2/Mgal), Emission (Tons CO2/Yr), and Power Supplier Emission Coefficient (Tons CO2/MWh)						
OBJECTID	StationN_1	WpumpF	WpumpE	WpumpEMB	WpumpEC	WpumpEI	WpumpEm
212.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
213.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
214.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
215.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
216.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
217.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
218.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
219.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
220.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
221.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
222.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
223.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
439.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
440.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
441.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
442.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
443.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
679.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
680.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
681.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
682.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
683.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
684.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
685.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
686.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
687.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
688.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
779.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
780.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
781.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
782.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41
783.00	RT50	1605.93	784.50	0.49	0.49	0.24	384.41

Appendix I: Statistical Analysis

The regression analysis for two graphs of Energy- Demand, and Emission- Demand were performed and the results are tabulated below. The regression analysis was conducted by the LINEST function of the Excel spreadsheet software. The accuracy of the line drawn depends on the degree of the scatter in the GIS generated output. The LINEST model generates the best straight line that fits the data and it uses the method of least squares for determining the best fit. An important calculated statistical parameter is the coefficient of determination (r^2) and standard error for Energy and Emission variables. The range of the coefficient is between 0 and 1. A value of 1 shows a perfect correlation in the data between the actual data and the predicted values and is indicative of an appropriate regression equation to be used for prediction of "Energy" use and "Emission" generated.

$$\text{Annual energy used} = \text{m1} * \text{Water Demand} + \text{b}$$

$$\text{Annual emission generated} = \text{m2} * \text{Water Demand} + \text{b}$$

Statistical Parameter	**Energy Used**	**Emission Generated**
Slope of line (m)	5.13	2.62
Y- intercept (b)	0	0
Standard error	0.186	0.091
Coefficient of determination (r^2)	0.978	0.980

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