IMPACTS OF URBAN FORM ON CENTRALIZED AND DISTRIBUTED WATER DISTRIBUTION NETWORKS

by

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(Under the Direction of Ke Li)

ABSTRACT

With the aging of our national infrastructure system and the challenge of developing resilient and sustainable infrastructures for future, the interdependence of water/energy system within the natural and built environment is critical. It was not until recent that the impact of urban form on the efficiency of water/energy infrastructure gained the attention of infrastructure engineers. The impact of three urban forms- sprawling, monocentric and polycentric, on the centralized and distributed water distribution networks were studied based on a synthesized city. Pumping costs savings of 68%, 71.5% and 55.3% for sprawling, monocentric and polycentric urban forms, respectively, was observed for the distributed than centralized water networks to satisfy the same water demands. This study also highlights the importance of ideal siting of water treatment plant locations, city elevation and population density, while planning an urban water infrastructure.

INDEX WORDS: Centralized water distribution, Distributed water distribution, Pumping costs, Urban forms

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ENERGY AND COST ANALYSIS OF CENTRALIZED VERSUS DECENTRALIZED

WATER DISTRIBUTION NETWORKS FOR AN URBAN SETUP

by

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DEDICATION

I dedicate this research to my Father, K. Prakash Rao, who is my motivation and my guide since childhood. I will be very happy to show my degree to dad, whose dream was to educate his daughter and to see her make him proud.

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INTRODUCTION

1.1 Water infrastructure planning and its impacts on distribution efficiency

Sustainable water supply requires integrated efforts of water resource management, treatment technology innovation, and water distribution networks planning and operation. Efficient water treatment and distribution technologies can reduce consumptive use of the existing water resources. Currently, the American Society of Civil Engineers' Report Card 2009 for America's infrastructure (ASCE 2009) reported very poor grades to all water-related categories of the United States: dams were assigned a D, inlet waterways, wastewater and drinking water infrastructures were all assigned D-grade (a failing grade). This shows that there is a large scope for improvement of the current water infrastructure in order to meet the current water demands now as well as in the future.

It has been estimated that about 75% of the cost of municipal water processing and distribution is incurred because of electricity in the United States (USDOE, 2006). Water distribution networks, specifically, consume a large amount of energy for treatment and distribution. Four percent of the United States energy electricity is expended in the treatment and transportation of water as well as wastewater. This accounts for 80% of the municipal water processing and distribution costs incurred (Electric Power Research Institute, Inc., 2002). In order to meet the increasing water demands of the population, it is expected that by 2025, nearly 3 billion people will need to be connected with water supply and about 4 billion with sanitation, thereby increasing the electricity consumption of the water and wastewater sectors by 33% (WHO and UNICEF, 2000; Alliance to save energy, 2002). About 80-90% of the average water utility's carbon footprint is ascribable to the use of electricity and 91% of the electricity use for surface water plants, is essentially for pumping (Carlson & Walburger, 2007).

But owing to high capital investments involved in distributed technologies, the centralized technologies are generally more widely accepted. Recent spur in smaller-scale technologies have produced more interests in distributed technological application and even more the conjunctive use of both centralized and distributed technologies. This co-use of both technologies would add benefits of both, to more closely achieve the desired goals. Water industry has been able to successfully use centralized treatment facilities in order to meet the water quality goals, usually water quality has to be assumed to be of desired standards till the treated water reaches the end users. Of late awareness has increased on water quality degradation within water distribution networks. Detailed research on efficient water treatment as well as micro-power generation technologies has turned the attention of city planners to utilize distributed water distribution systems (Norton & Weber, 2006).

Keeping in mind that water distribution systems must meet minimum requirements in terms of source transmission and distribution, storage and treatment, water distribution networks are planned for urban setup. Once the water network has been designed, the decisive factor for the choice of water distribution network is generally the cost of setting up, and maintaining the various hydraulic elements within the network. The minimum cost design of water distribution systems requires the conciliation among a variety of parameters such as- water demand types, daily demand pattern, pump scheduling pattern, tanks sizing and its function.

For urban water distribution systems, a series of interconnected closed loops were preferred, to guarantee the delivery of water to the public even under conditions of pipe failures. This is owing to the fact that looped topology allows the factors of redundancy and to some extent, even resilience. The case with gravity-driven water distribution systems is that for optimization limited to the cost of pipes, results in the minimization of pipes; and a tree network is produced. But any pipe failures in the tree network has severe consequences, so designers have used the idea of topological redundancy by the addition of pipes and closing of loops, to be able to provide water flow an alternative path to follow in times of failures (Todini et al., 2000).

In municipal water distribution systems, geography, climate and demography play a deterministic role in achieving energy efficiency. While upgrading the existing water networks, taking into consideration the changing population and urban configurations, the expansion projects are usually “pieced together” to develop the water distribution network. This would result in less efficiency when all the pieces are forced to work together (Tarquin, 1989).

The excessive use of energy in every realm of water supply is a direct indicator of the excessive resources (material, energy etc.) consumed and the amount of air, water and solid-wastes pollutants produced (Filion, 2004). For the overall system, significant energy saving is possible by improving the pumping performance, electricity demand, operation and maintenance and building-related energy efficiency (Aldworth, G.A, 1983). In order to strike a balance between the various factors, while planning, changes can be made in the following areas:

- Water system operating policies (Brailey and Jacobs, 1980; Walski, 1984),
- Effective storage utilization, (Brunzell, 1983),
- Pumping only during off-peak hours (Chao, 1979),
- Suitable pump selection (Aldworth, 1983; Walski, 1984)

According to Filion's study (2009), annual per capita pumping energy is higher than the cost of pipe fabrication, pipe repair and pipe disposal. Energy is a crucial environmental measure to understand the avoidable expenditures involved in water supply and distribution system. Energy consumption is proportional to the discharge and head directly, and inversely proportional to the pumps efficiency. Hence, the total cost of energy used by a pumping station in a year is given by,

$\Sigma(i=1 \text{ to } n)\ k\ Q_i\, h_i\ p_i\ F_i/\ e_i$

Where

Q_i = discharge at operationg point i

h_i = head at operating point i

e_i = wire-water-efficiency

F_i = fraction of time at operating point i

From this equation it is observed that energy savings is directly proportional to the volume of water pumped and the head against which the water is pumped. Utilities can save energy, by first conducting pump tests and an overall evaluation of pumping energy costs will determine the possible options for improvement in pumps' operation. Pump tests involve the calibration of all the meters and gauges within the network and also includes generating head and efficiency characteristic curves that is measuring wire-to-water efficiency (Walski, 1993). The only way to determine whether pumps are wasting energy is to test and identify the system head curves.

A decrease in pumped water or the system head would reduce the total pumping costs, as a whole. This was proved by Quindry et al. (1981), who observed that a 20% increased demand for the New York City water supply tunnels, produced reduction in node head throughout the system, thereby reducing pumping costs, too. Though, there is not much control over the volume that can be pumped into a defined pressure zone, the head/the total dynamic head (TDH) can be reduced. This TDH can be reduced by keeping the storage tanks at less than full capacity and the suction storage tanks at as full as possible, provided the operation point does not deviate too much from the best efficiency point for the pump (Rehis & Griffin, 1984).

Another way to cut down on energy costs is by clearly understanding the water demands within in the water network. Water demands vary considerably between water systems primarily to climatic changes, water system pressure, residential densities, water pricing, land use, and age of the distribution system. So for the process of estimating the future demands, the design engineer depends on reliable and accurate meter records of the existing water system for expansions or has to make use of analogous water systems for a new water system (WSDOH, 2009).

1.2 Necessity of considering urban form while water infrastructure planning

‘‘Towns and cities should be well designed, be more compact and connected, support a range of diverse uses within a sustainable environment which is well integrated with public transport and adaptable to change ’’*

Since the end of World War II, the type of urban growth has typically drifted away from city centers with high population and employment densities to lower population densities and land-use densities (Anderson et al. 1996). This development resulted in the separation of residential use from employment and recreation uses, thereby geographically dispersed cities with expensive urban infrastructure that consume substantial energy and material resources. This high environmental impact of cities and the predicted increase in urban population within the future generations is a driving force for the urban planners to change the urban form of modern cities. This would allow scope for efficient urban infrastructure development. But it is known that impact of urban form on different infrastructures plays a unified role in affecting energy use. For an urban setup, water infrastructure planning requires considering the factors of population size, serving area and initial cost investment, planning period (Eg.10-50 years) and design criteria such as minimum and maximum allowable pressures, pipe flows etc. This has been the traditional way of water infrastructure planning for several centuries, but recently studies have been carried out to incorporate urban development patterns while planning. The different population densities and the sprawling pattern play a pivotal role in determining the ideal size of water distribution network. Population density has been used as a representation of urban form on the study of infrastructure efficiencies.

* Towards an Urban Renaissance, The Urban Task Force, E&FN Spon, London, June 1999.

Steemers (2000) investigated transportation energy per capita to understand the relationship between densities versus transport energy. He showed that high-density cities such as Hong Kong have a low transport energy demand per capita, whereas Houston being a low-density city has a lower transport energy demand. In conclusion, dense cities are low energy cities, but it is not clear as to what extent density is the cause while the increased energy consumption is the effect. To quantify the relationship between population density and annual per capita energy use for water distribution systems, Filion (2009) developed an analytical model to quantify the energy used to fabricate, repair and dispose pipes, and pumping water in a mainline. His results indicated that a 10% reduction in annual per capita in the mainline could be achieved if the population density was increased from 10 capita/hectare to 275 capita/hectare. This is an indicator that, energy consumption is affected by density and it has to be included while planning the water distribution networks. Also, It is expected that in addition to the urban population density, the connectivity and the way of designing and locating the water network components plays an important role for the overall water network efficiency.

This relationship will play a significant role in deciding the choice of the type of water distribution network for the urban setup, too. Urban water management was categorized by Diagger and Crawford (2007) in three groups, centralized, decentralized, and hybrid (the combination of latter two water network technologies). Based on the size of the service area, water infrastructure can be classified as centralized and distributed systems. Traditionally, the centralized type of water distribution has been utilized to provide safe drinking water to the users. But specific drawbacks of this centralized system such as large investment cost (Harremoes, 1999), upgrading difficulties (Weber, 2005), and water quality issues owing to extended hydraulic residence time ((Okun, 2007; DiGiano et al., 2009), have emphasized the need to shift towards a more sustainable water distribution networks. The distributed water distribution networks may pose as a viable solution to this whole problem. On the contrary, distributed water systems were generally referred to as restricted, on-site and collection of wastewater systems (Crites and Tchobanoglous, 1998; Cook et al., 2009). This has taken a tremendous shift in idea, wherein; distributed water systems are being designed to incorporate wastewater, storm-water as well as drinking water. Case studies by Biggs et al. (2008) and Cook et al. (2009) highlight the benefits of distributed water systems from the Europe, U.S and Australia, using local water resources in terms of reduced costs, improved system reliability and environmental regeneration.

These recent efforts to understand the pros and cons of distributed water networks have shown there is a more plausible choice while planning the urban network.

1.3 Project research emphasis

The focus of this research is to study the energy efficiency of different water distribution networks with different urban forms. It is known that there is a direct impact of the type of urban form on the efficiency of infrastructure, which is further affected by various other factors such as geography, socio-economic factors, climate, and much more. A clear understanding on the impact of urban form and geographical factors on water distribution systems is necessary to meet the standards of energy efficiency, which is addressed in this research.

Two approaches to the type of water distribution have been considered:

1) Centralized Water Distribution System (WDS) - This type of WDS improvises the use of a single water treatment plant (WTP), pumping station and tank for the entire city for the required flow rate.
2) Decentralized or Distributed Water Distribution System (WDS) – The same required flow rate when equally distributed by five or more WTP', pumping stations and tanks, is another type of water distribution, called decentralized/distributed water distribution network.

As recent efforts are being taken to understand the impact of developing centralized vs. decentralized water distribution network. This research highlights the advantages and disadvantages of both types of water distribution system, by simulating the water networks for a synthesized city, developed based on the median US city population size.

CHAPTER 2

URBAN FORMS

"Urban forms can be defined as the spatial pattern of human activities at a certain point of time"- (Anderson et al., 1996)

Urban forms determine the location of services that drives material/energy flow. Therefore it is a key factor for the energy use and environmental emissions of urban areas (Anderson et al., 1996). Modern cities are developed around central hubs that support different types of industries, which attract the population to these work centers. There are several ways of classifying urban forms according to different points of view.

Metropolitan forms can be generally classified into three categories- density, diversity and spatial structure of the urban area. The overall shape of the metropolitan area defines the spatial structure, which characterizes land use patterns such as monocentric versus polycentric, centralized versus decentralized patterns and/or continuous or discontinuous land developments (Tsai, 2005). This spatial structure according to Bourne (1982) is comprised of three main elements- the urban form, the urban interactions, and a group of systematizing principles that represents the relationship between the afore-mentioned two.

Further, patterns of urban growth can be projected based on the 5-10 year increments in the land use within the defined region based on the existing land use database. When concerns about energy and environmental issues in cities are being considered, three archetypal forms- concentric, radial and multinucleated cities are considered. The focal point, common in all these forms, is the central business district. The concentric assumes a very dense transportation network. On the other hand, a more realistic urban form would be the radial city, in which regions of extensive land uses extend out from the central business district along major transport lines leaving less dense regions in between. But, recently, the multinucleated city has gained importance owing to the increase in several smaller central business districts, rather than a single huge one, owing to the limitations in employment, housing and transportation. Spatial connectivity is relatively possible in such an urban form as the transportation infrastructure would not necessarily be oriented towards the central business location, specifically (Anderson et al., 1996).

Similarly, Tsai (2005) described different types of sprawling metropolitan urban forms- monocentric, polycentric and decentralised sprawling, and quantified these hypothetical urban forms, at the same given population, population density, degree of equal distribution of activities, but different clustering patterns. Using these three urban forms, he differentiated compactness of the metro-cities from sprawling using density, correlating that larger the metropolitan area, the higher the density and degree of clustering of high density job areas.

Similarly, Filion (2009) has addressed three urban forms-radial, satellite and gridiron, to examine how water infrastructure is impacted upon by the spatial distribution of the population and its effects on the per capita energy consumption. Each of the urban forms, were assigned different patterns of high-density nodes and low-density nodes. Uniform population distribution has evenly spread low-density nodes at every 1km and no high-density nodes, whereas, monocentric has for-five high-density nodes very close to the source/reservoir and all other nodes are low-density ones. On the contrary, the polycentric population distribution has four high-density nodes located at the four farthest points in the network and another high-density nodes at the source, while all other nodes are low-density locations. Uniform, monocentric and polycentric population distributions were used to understand the impact of urban form on energy use. Based on the per capita energy consumption of every urban form, he has concluded that radial/monocentric population produced the lowest value owing to the compactness and multiple paths that addressed the needs of the population's demand which were more energy efficient owing to the closeness to the central water source.

Ideally, Filion's network is a very small network with a total pipe length of 60 km and doesn't consider the factors of additional energy savings over the 24-hour period simulation of a water network, and also how geography impacts the efficiency of the network. To incorporate these factors, this research derives inspiration from Filion's paper and three urban forms- monocentric, sprawling and polycentric (Figure 1) have been considered for this purpose. The centralized scenario (Fig 1 (a)) concentrates the population to the center of the city as compared to the uniform density (Figure 1 (b)), in which the entire population is evenly spread around the entire city. This scenario is identical to the concentric archetypal urban form described by Anderson et al (1996). The polycentric scenario is identical to Anderson et al's (1996) multinucleated urban form (Fig 1 (c)) clusters the population into five equal regions within the same theoretical city. The uniform density urban form is similar to Filion's (2009) uniform population distribution, wherein it is assumed that the population is assigned to every junction.

Similarly, centralized and polycentric urban forms are representative of monocentric and polycentric population distributions, respectively.

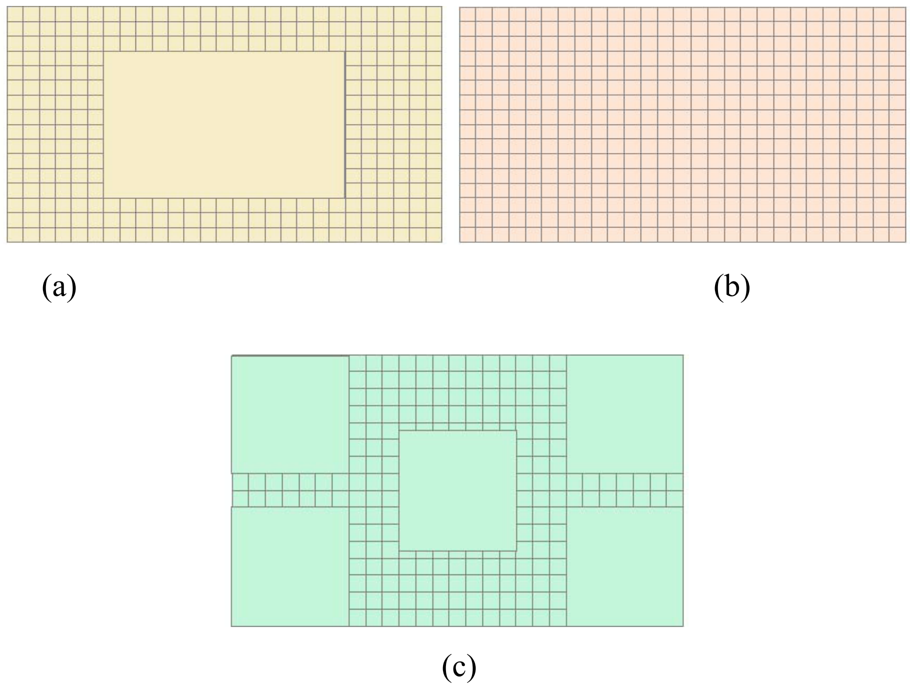


Fig 1. The urban form scenarios- (a) Monocentric, (b) Sprawling, and (c) Polycentric

With the layout of the city designed, the next step was to calculate the design population to inhabit the theoretical city, and represent the design flows and/or water demand for the junctions in the water distribution system. Each of the urban form was expected to represent a theoretical median sized US metropolitan city. US Census data (2009) was used to calculate the median population of the US metropolitan cities in Microsoft Excel. The median population size was computed as 171,000, but for calculation convenience, population of 170,000 was used as the population size of the theoretical city. Based on this computed population, the theoretical city was assumed to cover an area of 432 square kilometers. The representative urban forms were developed using spatial modeling tool ArcGIS 9.8. To cover the entire city, a 1kmx1km water grid system was implemented to be able to develop the water infrastructure, which will be discussed in the next chapter.

ArcGIS is a tool capable of integrating hardware, software, and data as well as display all forms of geographically referenced information. This allows us to visually understand, analyze and interpret data to understand trends, patterns as well as relationships in the form of maps. This tool, with is its interoperable nature with any other system framework or software (www.esri.com) allows a city's water distribution network to be inputted as an ArcGIS shapefile into Bentley's WaterGEMS-water modeling software, in which further hydraulic calculations can be carried out. Now, in order to develop the 1kmx1km grid system in ArcGIS, 'Create vector grid' tool in Hawth's analysis tool was implemented. This shapefile with a uniform grid system was considered to be the uniform density population distribution scenario. To create the monocentric and polycentric urban scenarios, the uniform density vector grid shapefile, was edited by using the Rectangle tool in ArcGIS. This rectangle tool helps to create a rectangular object in the shapefile, thereby covering the number of 1kmx1km square grids that were designed for the different scenarios. The dimensions-length and breadth, area covered and population density of every urban form has been tabulated in Table 1. The population density was calculated using the relationship,

Population density = Median population/ Unit Area (Number of persons per square kilometer)

The sprawling urban form has the lowest population density of 393.5 persons per square kilometers, followed by polycentric urban form with a population density of 809.5 persons/square kilometers. Amongst the three urban forms, the monocentric has the highest population density of 1133.3 persons/square kilometers. These different urban forms with such different urban population densities have helped to understand the impact of urban form on the water infrastructure development. Further, it must be understood that these three urban forms exist in real-time as a combination of two or all of the forms within the same city. This is instrumental to interpret the impact of urban form on a broader spectrum for the theoretical city as closer to reality.

Table 1. Urban forms dimensions and population density

Scenario	Length (km)	Breadth (km)	Total number of 1x1 sq. km of grids	Total Area (sq.km)	Population density (No. of persons/sq.km)
Sprawling	27	16	432	432	393.52
Monocentric	15	10	150	150	1133.33
Polycentric	Four corners: 6x7 blocks Center: 7x6 blocks		210	210	809.52

CHAPTER 3

HYDRAULIC SIMULATION USING EPANET 2.0

1.1 Introduction to water systems

The community water distribution systems in the United States serves about 95% of the population providing them with water that meets health-based drinking water standards. In 2007, 306 million people were served by approximately 156,000 U.S public drinking water systems (USEPA, 2007). The delivered water can be classified into the following broad categories-domestic or residential, commercial, industrial, public, and lastly water unaccounted for. In urban areas, 50% of water drawn is for domestic use, of which 90% of the consumers are domestic. Generally, water is used in residential centers for drinking and culinary uses, washing, bathing and laundering, heating and air-conditioning, irrigations, and for fire protection. To supply the required water, municipal water distribution systems comprise of the following steps:

- Collection of water: Tap a source capable of providing adequate water supply
- Purification/treatment: Based on the quality of the source water, the treatment process makes the water fit for human consumption.
- Transmission: Carry the collected and purified water supply to the community
- Distribution to consumers/end user: Dispense the transmitted water to the consumers in required amounts at suitable pressure.

1.2 Introduction to Water Distribution Networks

Water distribution networks from the water source to the consumer, primarily comprise of the interconnecting pipes, reservoirs, pumps/pump stations, valves, and elevated storage tanks. Of these hydraulic elements, the pumps, valves and turbines, are examples of the active elements, which can be operated to control the flow or pressure of water within the networks, while, reservoirs and pipes fall under the category of passive elements, as they cannot be directly controlled (Cembrano et al., 2000). Even though the size and complexity of water distribution systems are different, every network has the same function of delivering water from the source to the user.

These active and passive elements are commonly categorized into two broad components: physical and non-physical. The physical components consisting of the pipes, pumps and control valves collectively known as the links and junctions, tanks and reservoirs, which are connected to each other by the links.

Brief description of the physical elements-

Junctions:

The nodes in the network where links meet one another and the entry and exit of water occur. The elevation (above mean sea level), water demand and initial water quality are the basic inputs required to obtain the hydraulic head, pressures and water quality as outputs for every stipulated simulation.

Reservoirs:

The reservoir serves as nodes to represent an infinite external water source that provides water to the water distribution network. This node requires the hydraulic head, surface elevation and initial water quality for analysis.

Tanks:

These are storage nodes, capable of analyzing the variation in the levels of stored water volume over time for a hydraulic simulation. Tanks require the bottom elevation, diameter, initial, minimum and maximum water levels, and initial water quality as primary inputs.

Pipes:

Pipes serve as the links to convey water from one location to another within the network. The start and end nodes, diameter, length, roughness coefficient, and status are the important hydraulic inputs for the water distribution network simulation, which compute the flow rate, velocity, head loss, Darcy-Weisbach friction factor, average reaction rate and average water quality.

Pumps:

The most important link in the water distribution network that imparts energy to water in order to raise its hydraulic head is the pump. The start and end nodes and most importantly its pump curve are inputs for a pump. Defining a time pattern of relative speed settings can vary the pumps operation and help in computing the energy consumption as well as the pumping costs.

Valves:

The limiting of pressure or flow at specific points in the networks is the function of valves. The diameter, start and end nodes, setting and status are the inputs required to obtain flow rate and head loss as the outputs after simulation.

Non-physical components

Curves:

The relationship between two quantities can be represented conveniently using the curves. EPANET allows the use of pump curve, efficiency curve, volume curve and the head loss curve.

In this research, the pump curve has been primarily used which represents the relationship between the flow in Liters/second along the X coordinate axis and the head in meters, along the Y axis of the plot, predictive at the pumps' normal speed setting.

Time patterns:

The time pattern is a collection of multipliers applied to a specific quantity that is representative of variation over time. Primarily, nodal demand and pump schedules are important time pattern inputs required for simulation. This pattern helps to unify the changes in water demand with seasons, days of the week and hours in a day.

Controls:

The controls, namely, Simple and Rule-based, are statements which can determine the network operation, over time.

Emitters:

Emitters are generally used to model the water flow through sprinkler systems and irrigation networks, but can also be applied to simulate any leakages in pipes connected to a junction or process the fire flow at the corresponding junction (Rossman, 2000).

Generally, two types of water mains distribution patterns are observed in a community, (a) branching pattern with dead ends, and (b) grid iron pattern, with a central feeder of a looped feeder (Shammas and Wang, 2011). Encompassing all the various elements of the water distribution system, the basic steps employed during the development of one of the types of water distribution system are:

i. The water system's design period has to be determined (typically 20 – 30 years).

ii. The projected demand of existing consumers from current date up to the final design year has to be calculated/predicted.

iii. All anticipated developments that add to the demand step, need to be added to the water model for all the years until the design model year.

iv. Design criteria, such as maximum and minimum allowable pressures, maximum pipe flow velocities, preferred pipe diameters, storage requirements, etc. need to be set up.

v. Based on predicted demands for the final design, as well as including all the anticipated nodes and links required to supply present as well as future developments, the model has to be designed.

vi. The identification and investigation of various network configurations and the interpretation of future supply objectives in terms of cost minimization and reliability of supply.

vii. Lastly, the optimal design will be selected, ensuring the system variables meet the design criteria favorably.

viii. Once the final design has been defined, the demand in the model is progressively reduced, and at each time step, as many possibly removable components are changed whilst maintaining the design criteria. Repetitively, this step is carried out from the future prediction to the current water distribution network to finally achieve an effective system capable of meeting the needs of the present as well as the future growth (Ilemobae and Stephenson, 2006).

For system design and optimization that includes the active and passive elements, several methodologies have been proposed in the years and recently developments in these methodologies have been made as well. The earlier optimization models lacked the ability for designing and analyzing a complete water distribution system, and of them, Alperovits and Shamir (1977), Quindry et al. (1981), Morgan and Goulter (1985) and Lansey and Mays (1989) provided useful models pertaining to limited areas. The size of the network, the number of loading settings being analyzed, and the various components being designed- are the key areas to be focused on while water distribution modeling. Alperovits and Shamir's (1977) approach to considering various components in the distribution network optimization is strictly limited to the size of the system and the number of loads that can be handled. In addition to this work, Quindry et al. (1981) improved upon the limitations by ably expanding to a larger system but the limitation of including only pipes in the design posed a difficulty to analyze multiple loads. To overcome this shortcoming, Morgan and Goutler's model (1985) used a heuristic approach to consider multiple loads to define constraints, and were again limited by the problem of not being able to add costs to the objective function, as well as to run every model several times to reach the solution. Lansey and Mays (1989) presented a methodology to overcome these shortcomings, based on the concept of optimal control theory, which allowed the detailed analysis of the system components under various loading conditions along with the reduction in the constraint size, which would cater to large water distribution networks with large component numbers.

When designing or improving a system, the possibility that the system needs to function even when components are out of service (such as in the case of a pipe break, power outage, natural disaster, or off-line equipment) should be considered. The precision of hydraulic models depends on how accurately they have been calculated. The calibration parameters include pipe roughness, pipe diameter, and the demands and the model calibration relies on accurate field measurement data. The field measurements of system pressures, flow rates in pipes, tank water levels, valve status-open or closed, and pump speed and its operating status are important information to calibrate models.

The defined goal of an optimal water distribution system design is to be able to achieve maximum benefits of the developed system and at the same time keeping the costs at the lowest. It is known that for new pipe or rehabilitation needs of old pipes in a water network, are based on the following hydraulic parameters as input (Shammas & Wang, 2011):

- Minimum and maximum allowable pressures
- Minimum and maximum allowable flow velocity in pipes
- Demand requirements, and additional demands (if any)
- Status change requirements for pipes, pumps, valves, tanks, etc.

In addition to peak/maximum flow in the pipes, the ratio of the peak to average flow (P:A) and the relative cost of construction and energy (C_r) are two most important variables in water planning (Walski, 1980).

The cost for energy and construction is given by

$C_r =$ ENR* Construction cost index/ price of energy

Where, ENR=Energy News Record and the price of energy is represented in ¢/kW.h.

The importance of average flow is that it's the indicator of the actual flow in the pipe that is capable of determining the head loss and the energy requirements throughout the life of the pipe. The cost ratio, C_r, is indicative of the relative tradeoff between energy as well as construction costs. Ideally, selecting a larger pipe is cost-efficient if energy costs are high. Also, Lingireddy (1998) defined the peak flow (Q_p) and the average flow (Q), for a defined number of users being delivered water by a single pipe as,

$Q_p = K_p Q$

Where, K_p is the peak coefficient.

Given energy is the input to the system at source; energy is lost during transmission via valves and greatly at customer taps. Some energy losses are inevitable such as the frictional and minor losses within the water distribution network, owing to smaller pipe sizes or network configurations. Water utility planners, today, make use of hydraulic simulation models such as EPANET, WaterGEMS etc. to plan their city's water network, make improvements and manage water resources efficiently (Boulos et al, 2006; Walski et al, 2003). These models employ the laws of conservation of mass and energy to determine the spatial and temporal distribution of flows, pressures, energy losses and various other parameters within the distribution network with network specific demand patterns and operating conditions.

EPANET 2.0, a computer program capable of performing extended period simulation of hydraulic and water quality behavior within pipe under pressure constraints, allows the clear understanding of the movement and the fate of drinking water elements within the water distribution systems (Rossman, 2000). The conservation of flow equation for every junction and the head loss relationship across each link within the network allows the calculation of the heads and flows at the particular point in time, which is carried out iteratively by EPANET that employs the "Gradient Algorithm". This solution method initially estimates the flow in each pipe that need not satisfy the flow continuity equation, and by using a matrix new nodal heads are found iteratively.

With the water hydraulic simulation, carried out by EPANET, the optimal size of the pipe can be determined by selecting the pipe size as a function of peak flow, alone, wherein the diameter of the pipe can be represented mathematically for velocity (Walski, 1983) as:

$D= \sqrt{1.96Q/V}$

Where,

Q = peak flow (mgd)

D = diameter (ft)

V = velocity (fps)

Or, if the diameter were to be determined by the head loss at peak flow, the formula would be given as

$D= [42.7\ Q/C(h/L)^{0.54}]^{0.38}$

Where,

h/L = design head loss at flow Q (ft/100 ft) and C= Hazen-Williams C factor.

This is an approach to reduce pumping costs by reducing frictional losses within the pipes, thereby achieving energy efficiency.

1.3 *Methodology*

The theoretical urban city developed using ArcGIS 9.8 was used as a base-case scenario to develop a water distribution network in EPANET 2.0. In order to develop each of the scenarios required for the water network comparison, the following methodology was used:

Step 1: The system flow and tank size calculations were carried out for the theoretical city.

Water demand calculation, with maximum daily demand factor of 1.8 and 660 L/d/capita water consumption:

Maximum daily water demand = 660 L/day/per capita x 1.8 x 170,000 people = 2.0196 x 10^8 L/d = 2423.5 L/s

An average of the lowest and highest fire-flow demand was fixed as the average fire flow required.

The required fire flow in L/min was calculated as,

= (2000 + 45,000)/2 = 23,500 L/min = 391.66 L/s = 0.3925 m^3/s, for a duration of fire-flow assumed for 6 hours (Chin, 2000).

Therefore, the total water demand

= 2423.5 L/s +391.66 L/s= 2815.2 L/s.

Tank volume calculations:

Based on the per capita maximum daily demand factor of 1.8 (unit less), the total water demand required to meet the population of 170,000 people =2.0196 x 10^5 m^3/day.

According to Shammas and Wang (2011), the equalizing storage in a tank for constant pumping should be between 15-20% of maximum daily water demand. Further, any limitation of water supply may possibly raise the operating storage to work within a range of 30-50% of the daily water consumption.

1: For this research, 25% of the maximum daily demand was used as the equalization storage to account for any limitations with the 24-hour pump scheduling.

$25\% \times 2.0196 \times 10^5 = 50490\ m^3$

2: The fire flow demand (m^3) is added to the equalization storage volume.

The volume required for fire flow to be stored in the reservoir,

→ $V_{fire} = 0.3925\ m^3/s \times 6\ hr \times 3600\ s = 8477\ m^3$

The total water storage exclusive of the emergency storage, $50490\ m^3 + 8477\ m^3 = 58967\ m^3$.

3: The emergency storage is one fourth of the total storage. And, the subtotal is three fourths (75%) of the total storage. Therefore, Total storage = V_{total} = 58967/ 0.75 = 78622.67 m^3= 78623 m^3.

Tank level calculations:

For the total storage volume calculated, the maximum and minimum levels of water, as well as the diameter of the tank needs to be estimated. These calculations were calculated using Microsoft Excel, which allowed the easy calculation of tank water levels for corresponding diameters.

The total volume the tank can store for a period of 24 hours. Assuming the tank to be cylindrical in shape, the volume of the tank would be represented as

$\Pi \times (D^2/4) \times H$

Where,

D= diameter of the tank (m)

H= total Height of the tank (m)

The minimum level in the tank must be decided as per requirements in the system, and in this research 10-12 meters of head has been used. Based on this minimum volume of water that remains in the tank at all times, the height of the tank can be calculated.

Minimum/constant volume of water in the storage tank,

$V_{min} = \pi \times (D^2/4) \times h$

Where,

D= diameter of the tank (m)

h= minimum level/height of water in tank (m) = 10 or 12 m

The total height of the tank, H, can be calculated using the total storage volume of the tank, represented as $H = V_{total}/[\pi \times (D^2/4)]$

The maximum water level in the tank, $H_{max} = H - h$

Or $H_{max} = (V_{total} - V_{min})/(\pi \times (D^2/4))$

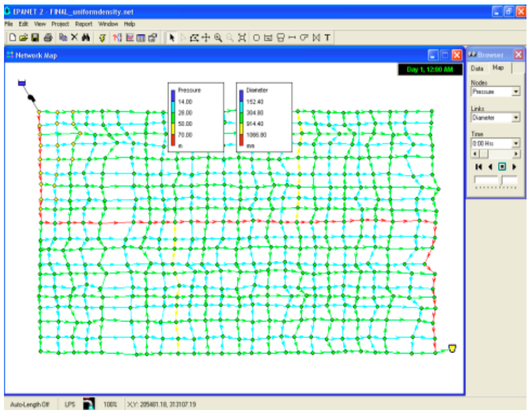
An Excel spreadsheet was generated to quickly compute the tanks levels using the above formulae, and to analyze the required diameter, D for the tank.

Step 2: The urban scenarios were imported from ArcGIS into EPANET 2.0, to develop the water distribution network frameworks. These shapefiles served as a background for developing the water network efficiently and also to set the right geographical coordinates for every point within the system.

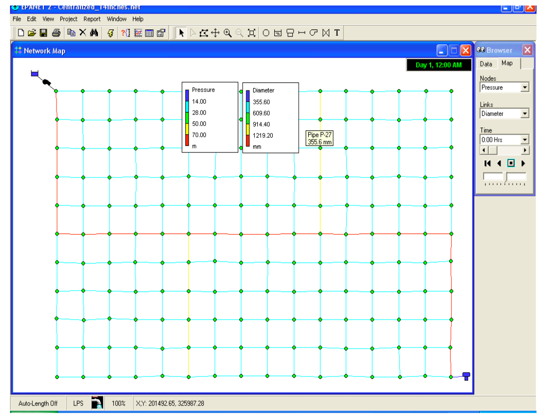
Step 3: The setting up of links and the nodes is the most important task while modeling as they are the representative elements of the actual water distribution network. Generally, two types of water mains distribution patterns are observed in a community, (a) branching pattern with dead ends, and (b) grid iron pattern, with a central feeder of a looped feeder (Shammas and Wang, 2011). For this research, the junctions were set at every corner of the 1kmx1km square grid, which when connected to each other by the pipes completed the looped or gridiron water network. The pipe diameters of the entire network were kept uniform to maintain consistency in pipe diameter sizes and ductile iron with roughness coefficient, 130 was used as the pipe material (Table 2). But the mainline pipelines were given a 1219.2 mm (48 inches) diameter size and an additional pipeline of 914.4mm (32 inches) sections connecting to the mainline were added to enhance the connectivity to the network (Figure 2). These mainline sizes served as the base case scenario for simulation. It is difficult to determine a design flow rate for a looped system, as the flow depends on the pipe size. Hence, pipe sizes were kept identical for comparison purposes.

Table 2. The base case urban scenarios and their corresponding water network pipe sizes

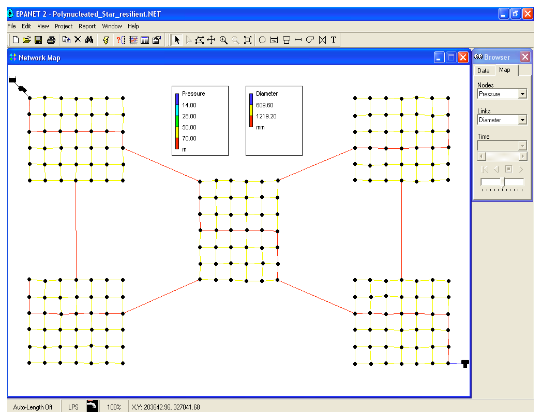
Urban scenarios	Network Pipe diameters
Uniform density	Interconnected pipe network of 152.4 mm (6”) and 304.8 mm (12”)
Centralized	A network of 355.6 mm (14”)
Polycentric	A network of 609.6 mm (24”)



(a)



(b)



(c)

(Note: The mainline diameter, 1219.2 mm in Red, and rest of the network, 609.6 mm in Yellow)

Figure 2. The three urban forms- (a) Sprawling, (b) Monocentric and

(c) Polycentric, with their mainlines.

Every urban form was assigned a centralized and distributed water distribution network to understand the impact of urban forms on water distribution network. With the defined looped water network, each urban form was allocated with a single or multiple water treatment plant (represented as the reservoir in EPANET) connected to the water network by a pump and tank/tanks for storage.

Centralized water distribution network:

The water network was kept the same for all the three urban forms, but several locations for the water treatment plant were assigned to clearly understand the impact of location of the reservoir on the water distribution efficiency. While the location of the water treatment plant was modified, the tank location was kept fixed at the lower right corner of the water network to maintain uniformity between different scenarios. The siting of the water treatment plant has been illustrated in Table 3.

Distributed water distribution network

With the same water network, multiple water treatment plants and tanks were assigned to every urban form, to represent the advantage of developing multiple treatment plants as opposed to a large centralized water treatment plant. The water for each of the distributed WTP's was assumed to be locally available. For both sprawling and monocentric urban forms, the same water demand of 2815.2 L/s was equally distributed between two, four, six and eight water treatment plants within the city connected to the mainline by additional pipelines of 914.4 mm (Table 4).

On the other hand, for the polycentric urban form, the five segregated water network regions were designated with two, three, four and five water treatment plants to supply the same water flow of 2815.2 L/s (Table 4). It is to be noted that the tanks were connected directly to the water treatment plants unlike the centralized water distribution scenario, in order to evenly split the storage volume required for the entire theoretical city.

Elevated water distribution networks

Both the centralized as well as the distributed water networks were given uniform slope of 1/1000 (0.1%), with an angle of elevation, θ equal to 0.057, to understand the impact of topography on water distribution networks. The height of each junction was calculated from the right most side of the network at zero elevation gradually increasing slope to the highest of 26.3 meters at the left most side of the network. The centralized network with the WTP at the upper-left corner and the tank at the lower right tank, and the distributed network with 6 WTP’s for sprawling and monocentric, and 5 WTP’s for polycentric were given elevated networks for investigation. The comparison of water networks with elevation versus the networks without elevation will help to understand the influence of geography on energy efficiency of water networks. The results of the comparison will be discussed in the next chapter.

Table 3. Different locations of the centralized WTP's for each urban form

(a) Location of WTP's for Sprawling Urban Form

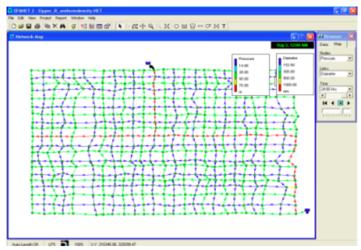
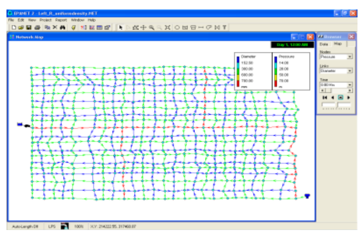
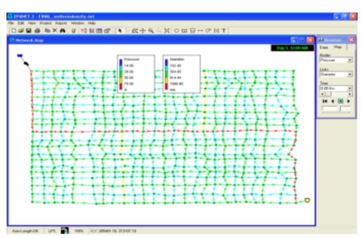
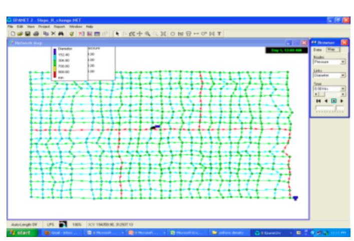
Network Scenarios	Location	Description
	Sprawling Urban scenario	
Case 1:Upper-middle WTP		WTP connected at the upper mid-point to the WDS, with additional pipes to connect to mainline
Case 2:Left-middle WTP		WTP connected to the left-mid point connected to the mainline with no pipe modifications
Case 3:Upper-left corner WTP		WTP at upper left corner in the city connected to the mainline directly as the base case water network
Case 4:Middle WTP		WTP at the heart of the city connected directly to the mainline

Table 3 (b) Location of WTP's for polycentric urban form

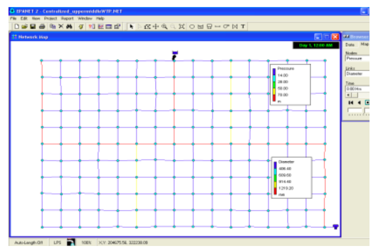
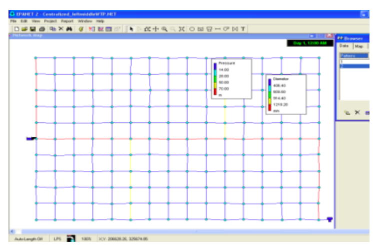
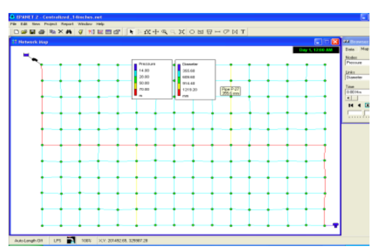
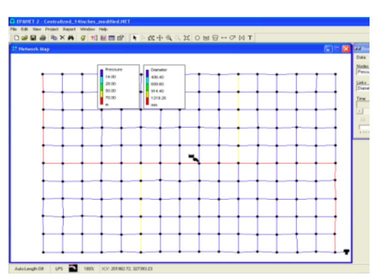
Network Scenarios	Location	Description
Monocentric Urban scenario		
Case 1:Upper-middle WTP		WTP connected at the upper mid-point to the WDS, with additional pipes to connect to mainline
Case 2:Left-middle WTP		WTP connected to the left-mid point connected to the mainline with no pipe modifications
Case 3: Upper left WTP		WTP at the upper left corner of the monocentric network
Case 4: Middle WTP		WTP at the center of the water distribution network

Table 3 (c) Location of WTP’s for monocentric urban form

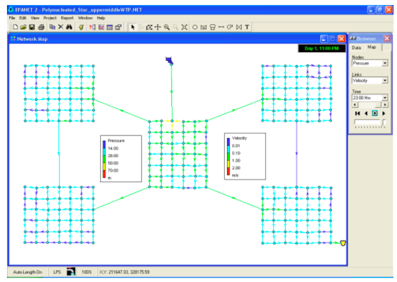
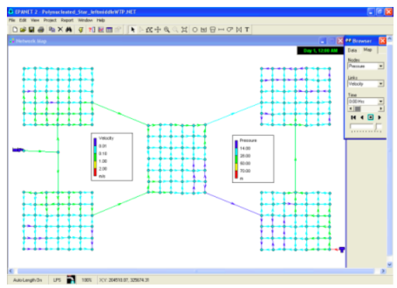
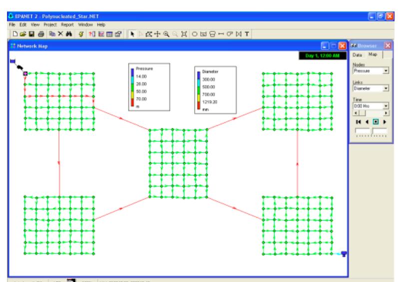
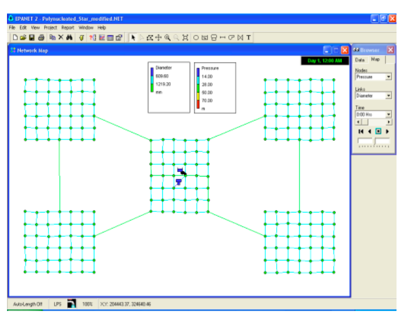
Network Scenarios	Location	Description
Polycentric Urban scenario		
Case 1:Upper-middle WTP		WTP connected at the upper mid-point to the WDS, with additional 1219.2 mm pipe to connect to mainline
Case 2:Left-middle WTP		WTP connected to the left-mid point connected to the mainline with 1219.2mm pipe connected to mainline
Case 3: Upper left WTP		WTP at the upper left most corner in the network connected to the mainline
Case 4: Middle WTP		WTP at the center of the water distribution network

Table 4. Different locations of distributed WTP's for each urban form

Table 4 (a) Distributed Water Distribution for Sprawling Urban Form

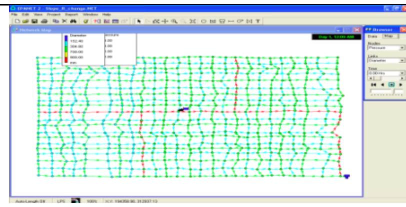
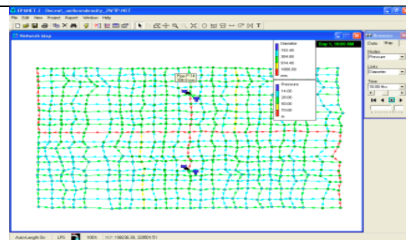
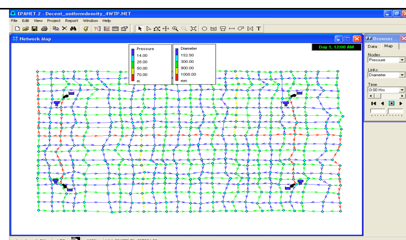
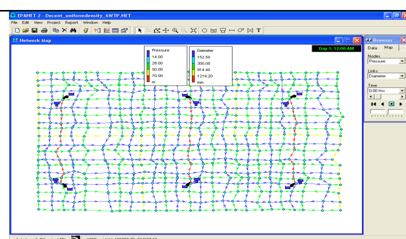
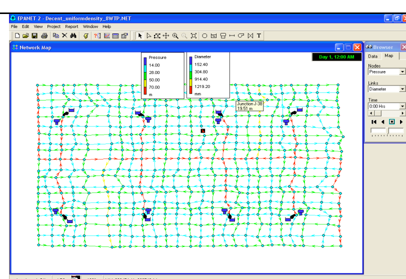
No. of water treatment plants	Location	Description
Sprawling		
1		A single WTP at the heart of the city
2		Two WTP's at the heart of the city connected to the mainline
4		Four WTP's at each of the four corners connected to the mainline
6		Six WTP's at ideal spaced locations connected to the mainline
8		Eight WTP's evenly spread throughout the city connected to the mainline

Table 4 (b) Distributed water distribution network for monocentric urban form

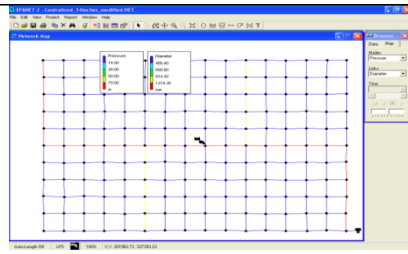
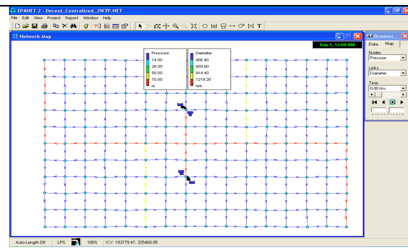
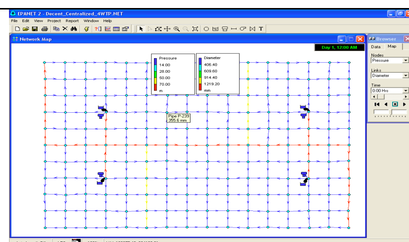
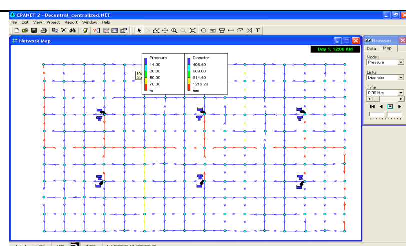
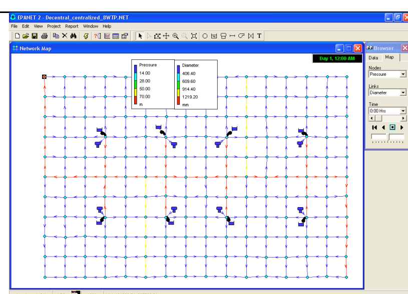
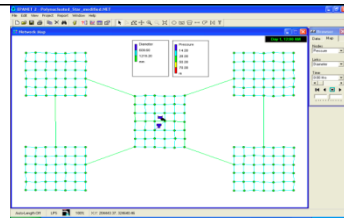
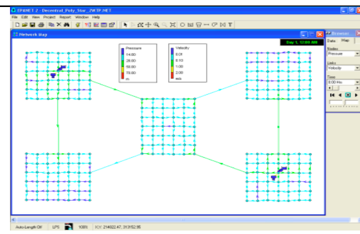
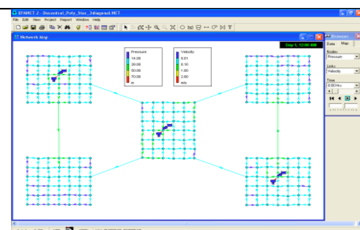
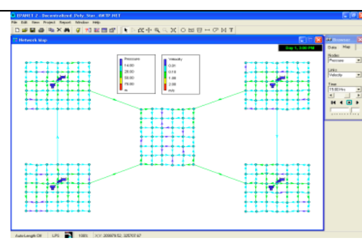
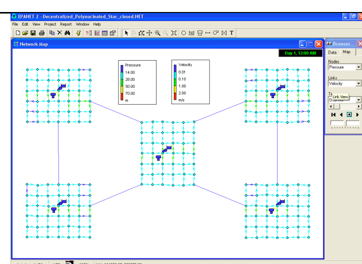
No. of water treatment plants	Location	Description
Monocentric		
1		A single WTP in the middle of the city
2		Two WTP’s at the heart of the city connected to the mainline
4		Four WTP’s at each of the four corners connected to the mainline
6		Six WTP’s at ideal spaced locations connected to the mainline
8		Eight WTP’s evenly spread throughout the city connected to the mainline

Table 4 (c) Distributed water networks for polycentric urban form

No. of water treatment plants	Location	Description
Polycentric		
1		A single WTP at the middle of the city
2		Two WTP's located at the upper left and lower right water network
3		Three WTP's located diagonally to the network supplying water to the distant cluster on the lower right via the middle cluster.
4		Four WTP's at all the four corner clusters, except the middle cluster.
5		Five WTP's at every cluster within the city

Step 4: EPANET 2.0 hydraulic simulation

With the junctions laid out and the pipes setup to connect every junction to the WTP and the tank, the water networks were subjected to simulation using the hydraulic simulation software, EPANET 2.0. The following inputs are required by EPANET to perform the proper simulation of the water models:

(i) Pump flow and head-

Initially the head is set to a predicted value and after iterative simulation the pump head-flow curve would be perfected.

(ii) 24-hour demand pattern for every junction-

The demand pattern for all the networks was kept fixed (Figure 3).

(iii) Tanks dimensions and elevation-

The minimum and maximum levels as well as initial levels need to be inputted along with the tanks' diameter and ground elevation. These values maybe iteratively modified as required by the simulation to meet the network's water demands.

(iv) Pump schedule-

The pump pattern is another important parameter that needs to be closely monitored to minimize over pumping of the water during the off-peak hours.

(v) Energy cost ($/kilowatt-hour)-

This is the cost factor used by EPANET to calculate the total pumping cost ($/day) for every 24-hour simulation.

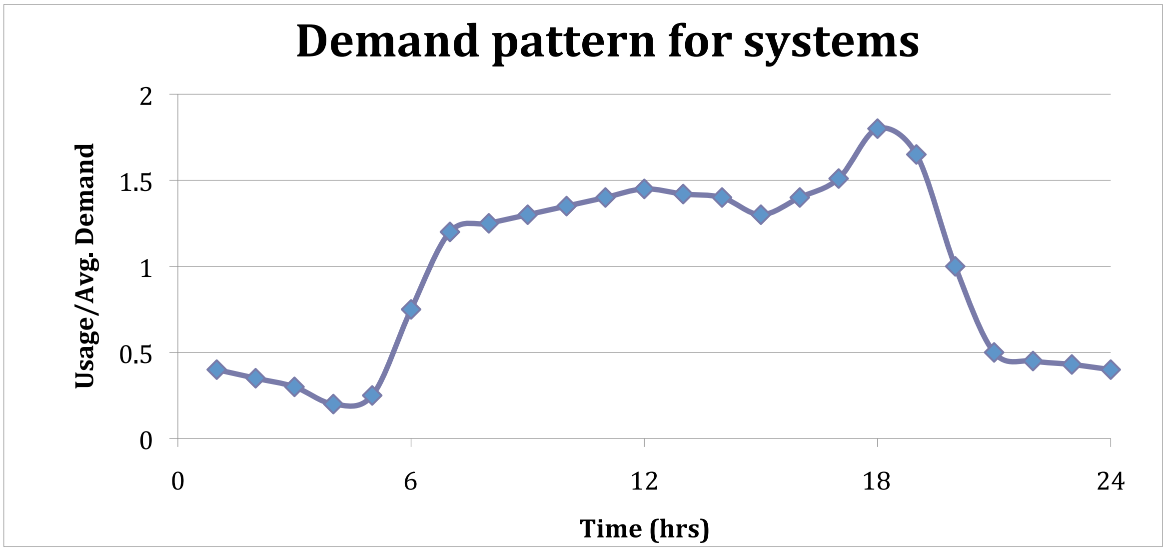


Figure 3. Base-demand pattern (Ghimire & Barkdoll, 2010)

After the preliminary steps, the network is ready for hydraulic simulation for a 24-hour period. The following parameters were kept as checkpoints for the water simulation procedure:

- The velocity in the pipes must be limited to 0.01 to 3.5 meters per second.
- The pressure at every junction should be within the range of 14-70 meters of head (20-100 psi).
- The tanks must have a minimum of 4-6 meters of water level fluctuation to ensure water circulation within the tank.

Keeping these checkpoints as indicators for a hydraulically sound network, the water networks were simulated in EPANET 2.0. If a run fails, the pump head and its pattern, the pipe diameters or the tanks elevation will have to be modified to ensure the successful run without violating those checkpoints are mentioned above. Finally, the pumping efficiency computed by EPANET can be finalized considering that no further changes can be made to the pumping pattern or the pump curve. For each of the simulated water networks, the pumping costs are recorded for comparison with other water networks.

CHAPTER 4

RESULTS

The water distribution network planning requires a clear understanding of the needs of the population (demography) and its growth pattern, geography and climate of the location. These are the pivotal factors to be considered while judging the size of the water distribution system. For this research, geography, population, and its growth pattern, were analyzed to test the suitability of distributed or centralized water distribution system for different urban setup. The hydraulic simulation results obtained from EPANET 2.0 serve as a start point to understand the relative impact of urban form on water distribution systems in terms of energy and/or cost efficiency. The results obtained from the research emphasize that pumping costs can be tremendously reduced by considering the geography and demography, while sizing the WTP's of the urban city.

1.1 Centralized vs Distributed Water Distribution System

Base scenarios comparison

In this research, a theoretical city was developed and both the types of water distribution networks were analyzed to prove the pumping efficiency of the distributed WTP over the centralized WTP. A single WTP located at the upper left corner of the theoretical city was used to represent the centralized water distribution system for all the three urban forms. On the other hand, four WTP's were setup to supply the same water demand in a distributed manner. The results are compiled in Table 5.

For all three urban forms, centralized water distribution systems (WDS) showed higher pumping costs as compared to four distributed WDS. For the centralized water distribution system, the sprawling urban form requires the highest pumping cost of 8309.3 $/day, which is 35% and 46 % higher when compared to that of the monocentric (5434.5 $/day) and polycentric (4492.94 $/day) urban forms, respectively. This is greatly due to the long pipelines that have to serve the sprawling population. The other issue with distributed demands is the maintenance of pipelines and leakage in the network. Over time, the wear and tear of the pipes degenerates the pipes longevity and requires the need to be constantly maintained and in extreme case, even replaced.

For distributed water distribution networks, the sprawling urban form still has the highest pumping costs, with its 2656.9$/day, followed by polycentric (2008.8$/day) and monocentric (1559$/day) urban forms. The difference in pumping costs between the urban forms shows a decrease because of the smaller service areas for each individual WTP. This comparison may not be conclusive because, as indicated later, the size of the service area determines the optimum number of distributed treatment plants.

The comparison (Figure 4) of the centralized and distributed network configurations depicts a minimum of 55% pumping cost savings for all the three urban forms. The monocentric and sprawling urban forms show similar reductions of 71.3% and 68% respectively. The polycentric urban form showed the lowest reduction in pumping energy costs (55.3%). Taking into account the service areas within the city, a general trend was expected with sprawling with the highest cost, followed by polycentric and then monocentric. But, monocentric form turned out as an outlier and showed a 17.3% higher pumping costs and a 22.4% lower pumping costs than polycentric for centralized and distributed water networks, respectively. This could be explained by the compactness of the monocentric urban form with higher population density required more pumping to meet the populations' 24-hour water demands.

For the distributed polycentric urban form, the mainline pipes of 1219.2 mm connecting the five clusters were setup with a control valve (CV), which remains closed until there is a shortage of water supply in any of the clusters. In addition it was also observed that the head loss was high within the clusters, itself, summed up to a value of 135 meters of head. This explains that the urban form has a direct impact of the polycentric urban form, considering the fact that the pumping energy requirements is much lesser for the sprawling and monocentric urban forms while applying distributed water networks.

Further it is to be understood that the distributed pumping costs do not take into consideration any external pumping costs, since localized water resources were assumed for the networks. It would be valuable to add these external pumping costs to the simulated distribution costs and compare with centralized water networks' pumping costs.

Yet, these results serve as preliminary findings to prove the advantage of distributed over centralized water distribution system. In general, a large reduction in pumping energy costs can be achieved by shifting to decentralized water distribution networks, though the number of water treatment plants required must be determined considering the size of the urban setup and topography.

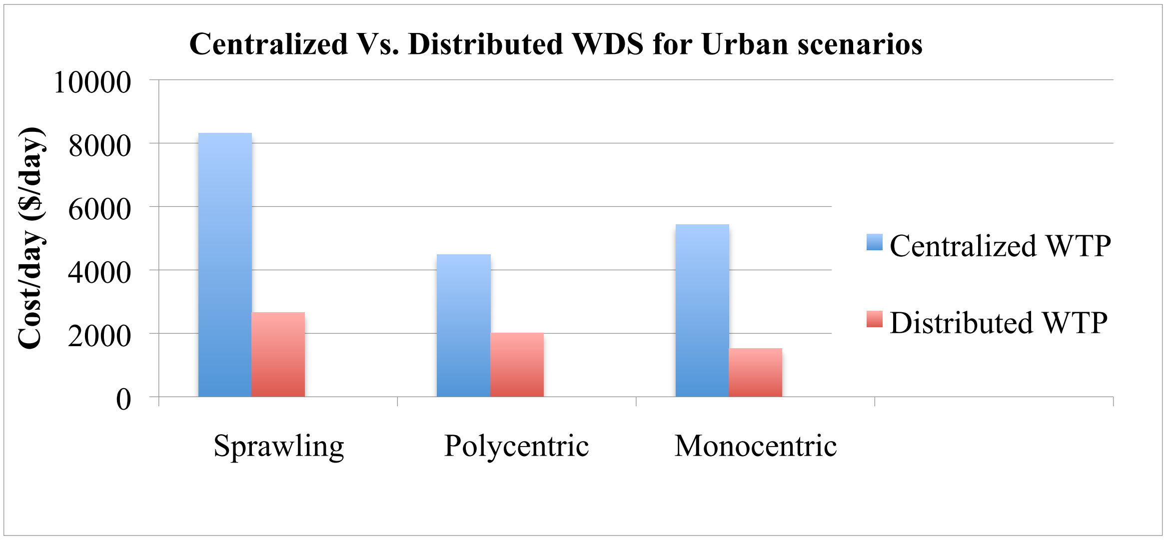


Figure 4. Pumping energy cost comparison of the centralized and decentralized water distribution network for each urban form

Table 5. Comparison of centralized versus distributed water distribution networks for each urban form

Scenarios	Centralized WTP ($/day)	Distributed WTP ($/day)	Centralized Vs. Distributed (%)
Sprawling	8309.3	2656.9	68.0
Polycentric	4492.9	2008.8	55.3
Monocentric	5434.5	1559.0	71.3

1.2 Location of WTP on pumping efficiency

The impact of siting of WTP on pumping efficiency for all the three urban forms has been summarized in Table 7. Each of the urban forms was designed with four identical WTP locations, namely, Upper-left, Middle, Upper-middle and Left-middle. The descriptions of each of the urban form locations are given in Table 4. The sprawling urban form has its entire population spread uniformly throughout the city, while the monocentric concentrates the same 170,000 people into an area of only 150 sq.km. This explains the reason why the impact of WTP location on the sprawling and monocentric urban forms shows an identical pattern (seen in Figure 5). But the polycentric urban form with its five segregated clusters serving the same population size has its topological differences owing to the large area to be covered to reach the population living in the clusters. This also strongly emphasizes the impact of urban forms on pumping costs.

A great difference was noticed in the pumping costs between locating the WTP at the upper left corner versus middle of the city for the centralized water distribution networks. For example, in Table 7 (a), the upper left corner WTP for sprawling urban form showed 8309.32 $/day pumping costs, while the middle WTP showed only 4186.36 $/day, a 49.6 % reduction in pumping costs in changing the location of the WTP. Similarly, the polycentric and monocentric showed a 42.5%, and 39.4% reduction, respectively, while shifting the WTP from the upper-left corner to the middle of the theoretical city. This difference in pumping costs can be explained by the reduction in head loss in the system, for each of the three urban forms as seen in Table 6. The calculations were based on the longest path expected for water being distributed within the distribution system to follow. Sprawling, monocentric and polycentric urban forms shows a 47.8%, 52% and 51.4%, reduction in head loss respectively when the WTP was located at the upper-left corner versus at the heart of theoretical city.

In order to clearly understand the importance of WTP location to energy savings, the centralized water distribution networks for each urban form was modified to two other different locations. Table 7. (a), (b), and (c) describes all the three urban forms-sprawling, monocentric and polycentric, with their different WTP's locations. The reason for choosing these WTP locations is that these can be ideally used to represent the WTP at any other isometric locations within the same city. For the sprawling urban form, the upper-left corner WTP shows the highest pumping cost of 8309.32 $/day, which is 26.3% higher than upper-middle WTP (6124.5 $/day), 30% more than left-middle WTP (5786.7$/day) and 50% higher than the middle WTP (4186.4$/day) locations.

Table 6. The head loss for three urban forms with their WTP's at the middle versus at the upper-left corner locations of the city

Urban forms	Sprawling		Monocentric		Polycentric	
Location	Middle WTP	Upper-left WTP	Middle WTP	Upper-left WTP	Middle WTP	Upper-left WTP
Head loss*, h_f	73.7	141.1	41.0	85.2	65.6	134.9
Pipe length (m)	21625	41394	121027	24998.5	22250	39671.3

* Head loss, h_f, is given by the Darcy Weisbach's equation, $h_f = fLV^2/2gD$, where friction factor, f = 0.014 (unitless); Flowrate, Q= 2.8152 m^3/s; Diameter, D= 1.219 m; Area, A= $3.14D^2/4$; Velocity, V=Q/A=2.41 m/s and acceleration due to gravity, g=9.81 m/s^2.

In contrast, the left-middle WTP shows the highest pumping energy costs of 5544.9 $/day for polycentric urban form, closely followed by upper-middle and upper left corner WTP's with 4839.4 $/day and 4455.21 $/day, respectively, and the lowest pumping costs of 2554.6 $/day when the WTP is located at the middle of the city. As for the monocentric urban form, the upper left WTP with its pumping cost of 5434.5 $/day stands as the highest energy consumer, followed by upper-middle and left-middle WTP with pumping costs of 3784.4 $/day, and 3624.6 $/day, respectively. While, the middle WTP with 3294.4 $/day again showed the lowest pumping energy cost.

In summary, the highest pumping cost savings were seen in the order of - sprawling showing 50% reduction, polycentric showing 54% and monocentric showing 40% savings, while moving the WTP from the upper left corner location to the middle WTP location. Figure 5 shows an identical pattern of pumping costs for sprawling and monocentric urban forms, middle, left-middle, upper middle and upper-left corner WTP's, in the order of lowest to highest; but polycentric shows deviation from this pattern, with lower pumping costs for upper middle and upper-left corner WTP's. Considering the greater than 50% reduction in pumping energy costs, the distributed water distribution networks should be given higher preference over centralized water networks. Though there are huge capital-cost drawbacks in doing so, the long-term assurance of a functional and efficient water distribution system is alluring. It has to be considered that addition of operation and maintenance costs and capital costs to the low pumping energy is required to make the comparison more comparable. But it has to be kept in mind that lesser energy consumption would imply lesser pressure on the non-renewable fuel sources, thereby lower carbon footprint as well.

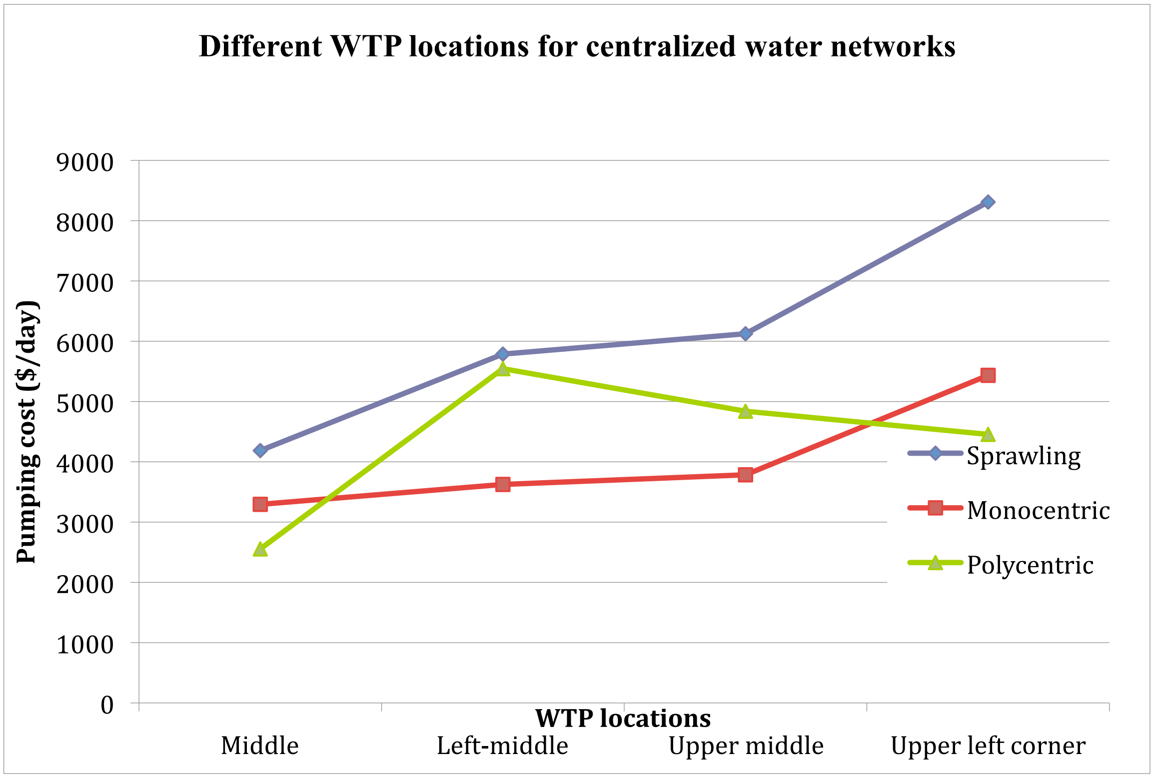
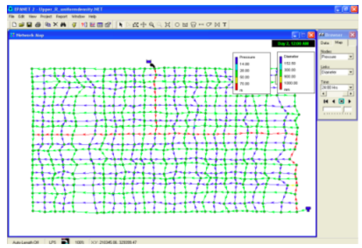
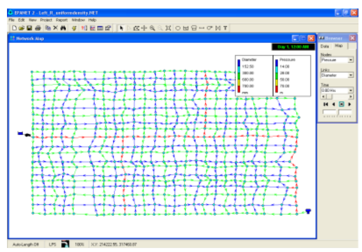
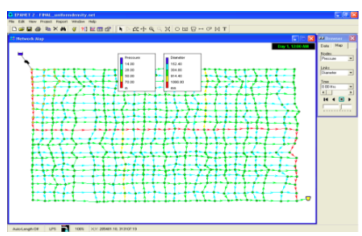
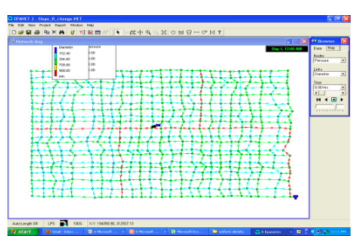


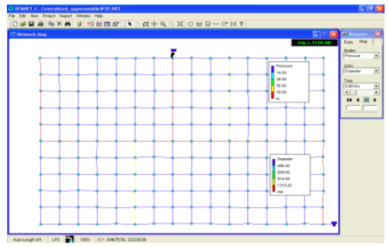
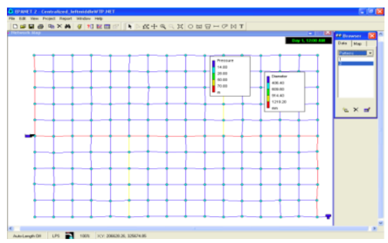
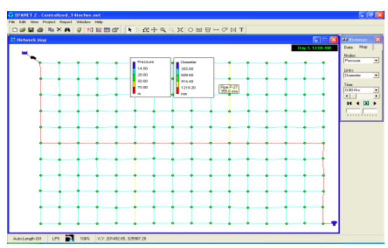
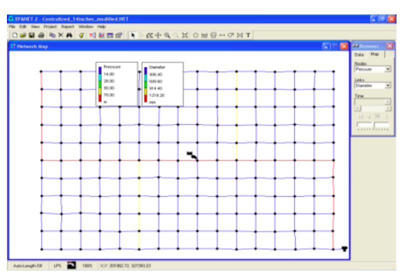
Figure 5. Centralized WTP locations and their corresponding pumping costs (in dollars per day)

Table 7. Different locations of the centralized WTP's for each urban form

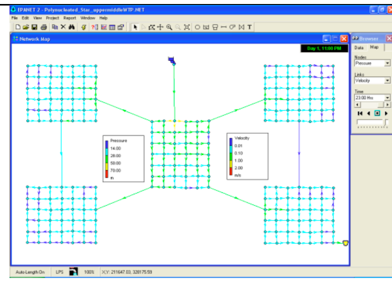
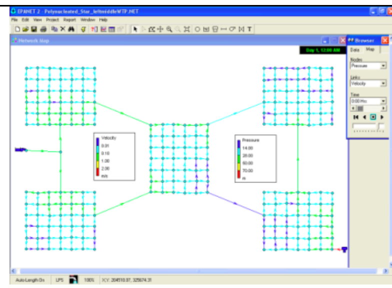
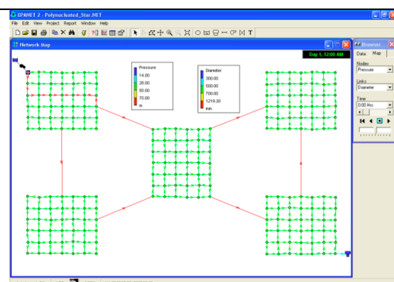
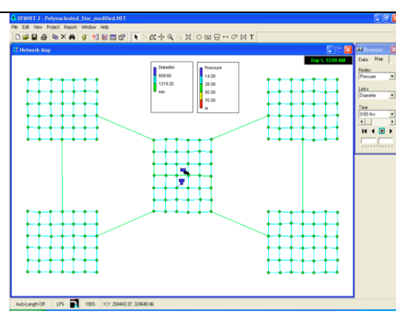
(a) Sprawling urban form- Different WTP locations

Network Scenarios	Location	Pumping cost ($/day)
Case 1:Upper-middle WTP		6124.5
Case 2:Left-middle WTP		5786.7
Case 3:Upper-left corner WTP		8309.3
Case 4:Middle WTP		4186.4

(b) Monocentric urban form- Different WTP locations

Network Scenarios	Location	Pumping cost ($/day)
Case 1:Upper-middle WTP		3784.4
Case 2:Left-middle WTP		3624.6
Case 3: Upper left WTP		5434.5
Case 4: Middle WTP		3294.4

(c) Polycentric urban form- Different WTP locations

Network Scenarios	Location	Pumping cost ($/day)
Case 1:Upper-middle WTP		4839.4
Case 2:Left-middle WTP		5544.9
Case 3: Upper left WTP		4455.2
Case 4: Middle WTP		2554.6

1.3 Pumping costs for different number of WTP's for distributed WDS

Population density as well as the size of the urban setup can help serve as a deterministic factor to select the number of treatment plants that need to be setup for the theoretical city. Location of the WTP's is another important factor to be considered while deciding the setup of the distributed water network. For this research, the sample number of the WTP's used for each of the urban form, listed in Table 8, have been given located at equidistant locations from one another. But it is to be noted that these locations may not be ideal sites for the WTP, since the demands for every junction is considered to be uniform throughout the system. Both sprawling and monocentric urban forms were designed with two, four, six, and eight WTP's whereas, owing to the topological limitations, polycentric was designed with two, three, four and five WTP's.

As seen in Table 8, a declining trend is seen in pumping costs for all the three urban forms as the number of WTP's located within the theoretical city was increased. The sharing of the water demand helped reduce the pumping costs considerably, as lower head was required for pumping at the same flow rate of 2815.2 L/s for all the systems. But for polycentric urban form with three WTP's showed higher pumping costs of 2256.2 $/day and is an outlier in the pumping cost pattern followed by the urban forms; thus a more ideal siting of the three WTP's in the polycentric urban form is necessary.

The setting up of number of treatment plants thereby, requires an understanding of the initial big investment and the operation and maintenance of more than one WTP for the city. In addition to this study, a cost and O & M study will help in predicting the number of WTP's that a city would need, with respect to the size of the city and the population to be served.

Table 8. The pumping costs of distributed WTP's for each urban form

No. of WTP's	Cost ($)/day
Sprawling	
1	4186.4
2	4203.8
4	2656.9
6	2157.5
8	1983.6
Monocentric	
1	3294.4
2	2277.7
4	2008.8
6	1770.3
8	1817.6
Polycentric	
1	2554.6
2	2188.3
3	2256.2
4	1559.0
5	1535.8

1.4 Impact of Elevation on WDS

The impact of topography on water distribution networks was understood by giving the theoretical city an even slope of 1/1000 (0.1%). This gradual slope with an angle of elevation, θ equal to 0.057 was used to calculate the height of the junction from the right corner of the theoretical city considered as the base with zero elevation. The highest point in the slope was calculated to be 26.3 meters above sea level.

This elevated approach helped to understand the effect of elevation/topography on pumping costs and network efficiency. Both centralized as well as distributed water networks were simulated for 24 hours for all three urban forms, and it was observed that adding slope reduced overall pumping costs.

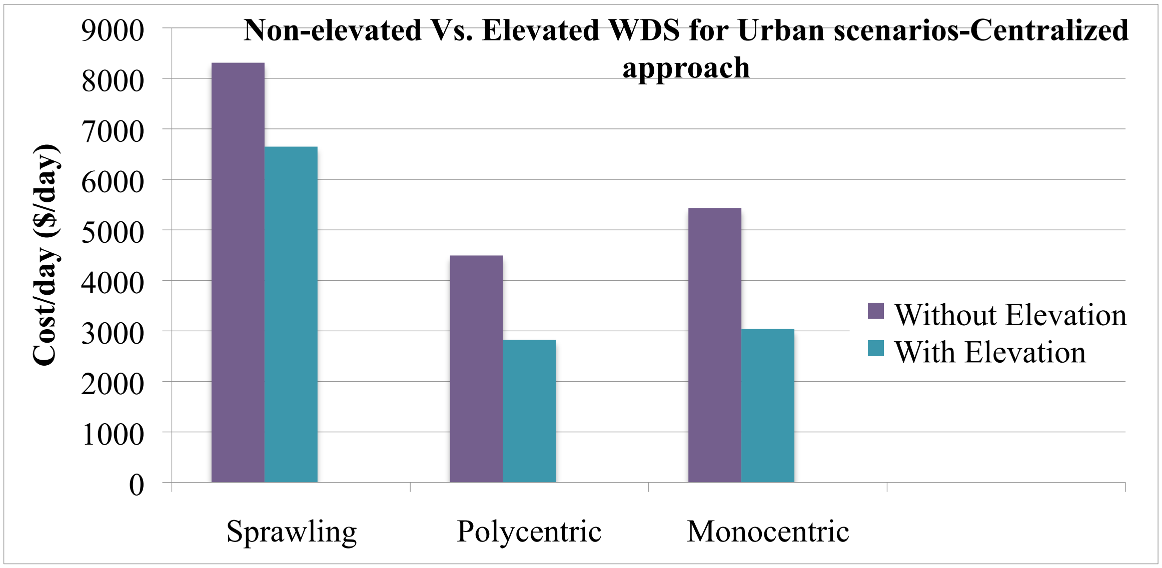
As seen in Fig 6 (a), an added slope for centralized water distribution networks resulted in the reduction in energy costs by almost 56% for monocentric, a 40% for polycentric and about the 20% reduction in energy costs for sprawling urban water infrastructure. Even for distributed water networks, a slightly different pattern is noticed by adding the slope, wherein, the monocentric distributed network seems to be more energy-cost efficient, with a 56% reduction, by the ascent in the network followed by sprawling with a 27.5 % reduction and the lowest pumping energy saving is shown by polycentric urban form with its 12.8% (Figure 6 (b)). The lowering in pumping costs (Table 9) is evidently caused by the reduction in pumping head requirements to meet the system's water demand when an ascent was assigned to the same water distribution network. Most importantly, the monocentric urban form with the highest population density proves to be the highest beneficiary by the addition of the slope to the theoretical city.

Energy usage is linearly proportional to the pump's horsepower, yet is dependent on the topography and head of the networks concerned. This was proven by Santosh and Barkdoll's (2010) study on the energy sensitivity of water distribution systems with variation in pump horsepower and location of pumping stations. The adding of elevation to the theoretical study and the observed reduction in pumping energy costs in this research, is in sync with the results reported in Santhosh's study, where savings were observed for networks with higher elevations. It was also suggested that smaller pumps with lesser horsepower and/or additional pumping stations result in energy savings that strongly corresponds to the lower pumping costs for distributing the same required water flow using more than one WTP. Thereby, it strongly is recommended to consider the geography/topology while planning an urban setup, in order to ensure more energy efficiency.

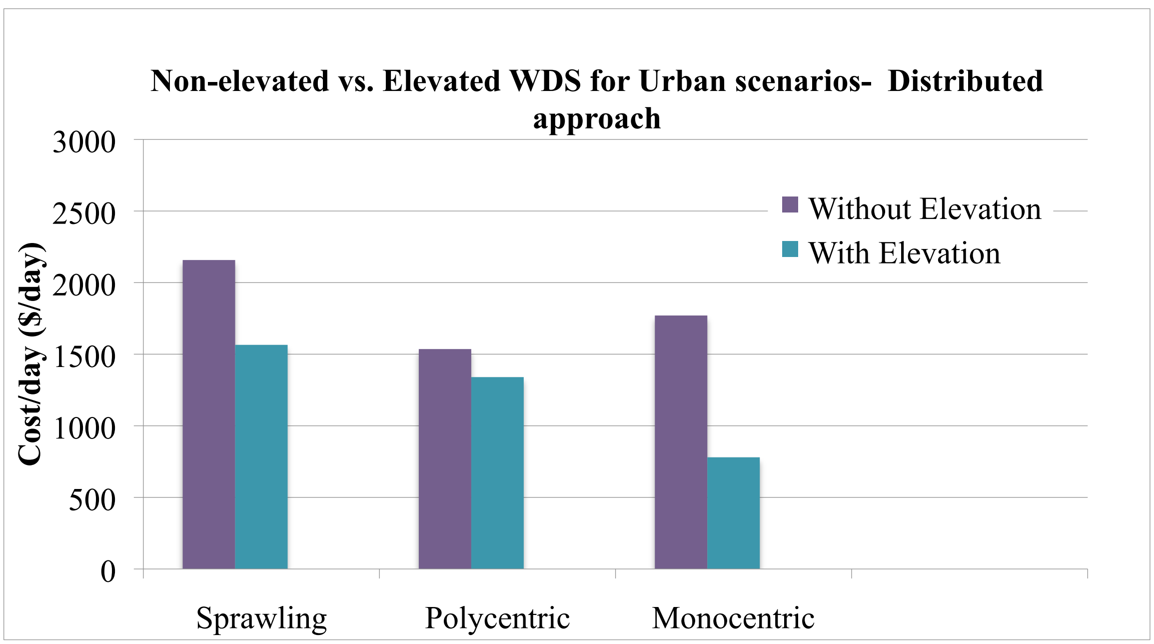
Table 9. Elevated centralized and distributed water distribution networks

Urban Networks		Pumping costs ($/day)	
		Without elevation	With 0.1% elevation
Centralized WDN	Sprawling	8309.3	6647.9
	Polycentric	4492.9	2823.6
	Monocentric	5434.5	3036.8
Distributed WDN	Sprawling	2157.5	1565.2
	Polycentric	1535.8	1339.9
	Monocentric	1770.3	779.9

For each urban form, further study was carried out on the impact of topography was performed, by adding elevation to the different WTP locations. From the results of ideal location of WTP, the Cases 3 & 4 pumping costs, from Table 7 of the centralized water distribution systems were selected as the data for this topography study.



(a)



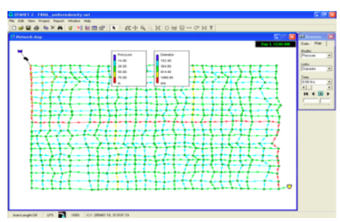
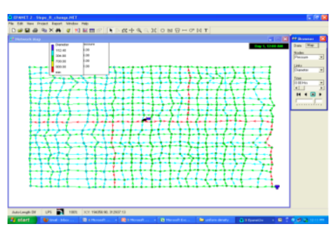
(b)

Figure 6. Non-elevated vs. Elevated Urban water distribution systems- (a) Centralized (with one WTP, pump and tank); (b) Distributed (multiple WTP's, pumps and tanks)

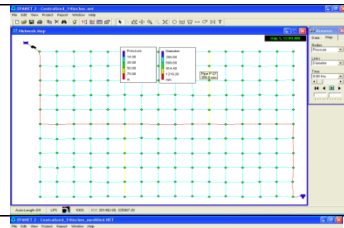
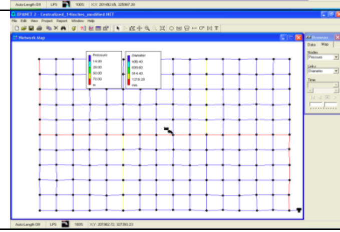
As seen in Table 10, for sprawling urban form, a reduction of 20%, and 13% pumping costs savings was observed for WTP at the upper left and middle locations, respectively. At the middle WTP, adding the elevation did not benefit the water distribution network, but instead has consumed 13 % more pumping energy. For monocentric and polycentric urban forms, adding an elevation to the networks with WTP's at two extreme locations showed pumping savings between 37-44%. The WTP at the heart of the city is beneficial in terms of energy cost even while topology is added to the water distribution network, with the exception of sprawling urban form, where not much energy savings was observed.

Table 10. Elevated Urban Forms With Different WTP Locations

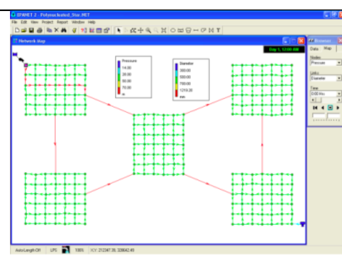
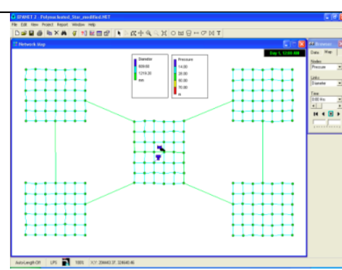
Table 10 (a) Sprawling Urban scenario- Elevated Vs. Non-elevated Scenario

Network Scenarios	Location	Pumping cost ($/day)		
		Without Elevation	With Elevation	Relative Diff. %
Case 1:Upper-left corner WTP		8309.3	6647.9	20
Case 2:Middle WTP		4186.4	4730.1	13

(b) Monocentric Urban scenario- Elevated Vs. Non-elevated Scenario

Network Scenarios	Location	Pumping cost ($/day)		
		Without Elevation	With Elevation	Relative Diff. %
Case 1: Upper left WTP		5434.5	3036.8	44.1
Case 2: Middle WTP		3294.4	1694.1	48.6

(c) Polycentric Urban scenario- Elevated Vs. Non-elevated Scenario

Network Scenarios	Location	Pumping cost ($/day)		
		Without Elevation	With Elevation	Relative Diff. %
Case 1: Upper left WTP		4492.9	2823.6	37.2
Case 2: Middle WTP		2554.6	1408.0	44.9

1.5 *Relationship of Urban City Size Vs Pumping Cost*

The energy efficiency is clearly dependent on the type of urban form as well as the type of water distribution network designed for the same theoretical city. Though this study focuses only on the pumping energy costs, additional maintenance and capital costs also need to be considered to understand the overall effect of the each urban form on water distribution costs. Thus, making amendments to urban forms does not by itself prove as a path to achieve energy conservation directly, but poses as a strategy for other means of conservation techniques. Technological changes can inevitably improve energy efficiency than just addressing land-use planning to conserve energy (Small, 1980). This would imply the per capita unit cost would reduce if the urban forms were planned considerately.

In the case of water distribution networks, pumping costs are directly dependent on the size of the population inhabited in the city and population density, i.e. number of persons per square kilometer. Density is a distinct dimension of metropolitan/urban forms and can ably characterize density- based sprawling patterns by measuring land consumption per capita (Galster et al. 2001). The city with an area of 432 sq.km was initially reduced to 1/2, 1/4th, 1/6th and 1/12th the size, for every urban form identically. To understand the impact of population on urban form, a factor of 2, 4, and 6 times the base population density of 393.5 persons per square kilometer had been used to increase the population density. Each of these cities was simulated hydraulically to determine their pumping costs per day using EPANET. Considering the impact of urban form on the per capita unit cost for pumping, Figure, 7 and 8, depict consumption trends based on two important urban form parameters- population density and population.

Figure 7 and 8 represent the relationship between population and unit cost at constant densities, for sprawling and polycentric urban forms. The unit cost for every gallon consumed by the city's population, given as dollars per unit kilo-gallon, is represented on the Y coordinate, while on the X coordinate, the size of the population inhabiting the city is represented. By keeping the population density constant for different population sizes, the per capita consumption was calculated and plotted.

Each of the urban forms show similar trends for population versus unit cost, proving that with the increase in population density the unit pumping cost appears to be increasing. But another important factor that plays an important role in determining the ideal size of the city that could be efficiently supplied is water distribution network size compatibility. The pumping costs show a relationship with the size and the population of the theoretical city. This highlights the need to understand the available city size and population while planning the water distribution network to ensure network efficiency. Since, for every network size there is a limitation of the amount of people it can provide water to, the breakpoint in design population while planning for future water distribution has to be considered. Hence, at a specific density, with a defined population, the unit cost can be predicted and the impact of urban forms can be analyzed using this prediction while developing a water distribution network. The prediction of the unit pumping cost helps to highlight the amount of energy savings that can be made since pumping consumes about 80% of energy for water distribution networks.

Another point to be highlighted in this regard is that, the unit cost of the water treatment plant would follow a declining trend as shown by Norton & Weber (2006), as the population size increased. If we combined the unit cost for pumping as well as the unit cost of water treatment into a same plot over the same population size intervals, the ideal size of the water distribution network as well as the distribution area to be covered by the WTP can be ideally predicted. Clearly it is possible to identify the ideal size of the water distribution network as well as identify the ideal size of the water treatment facility required for the same city.

It is to be noted that the impact of urban form versus population density studied in this research was limited only to centralized water distribution networks. This allows the scope to understand the pros and cons of developing distributed water networks for a given area with a defined population. In conclusion, it has been known that for each density, there is an optimum size for an urban water network as well as water treatment facility and one cannot shift to over-distributed or over centralized.

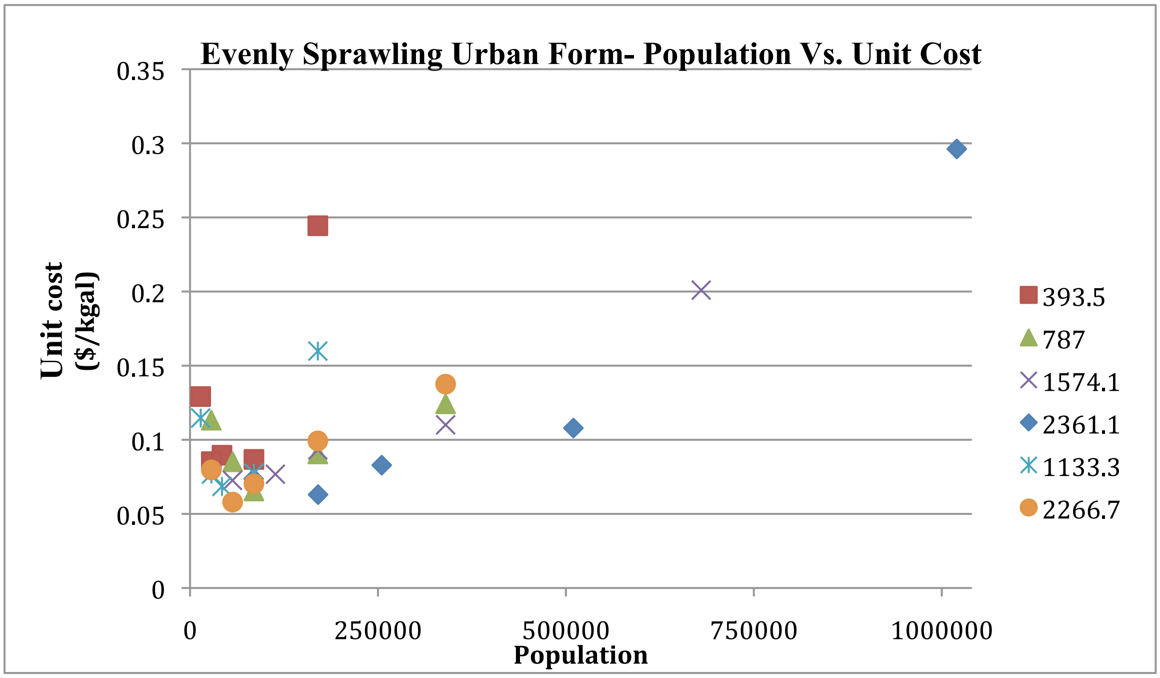


Figure. 7. Evenly sprawling urban form- population versus unit cost at different densities

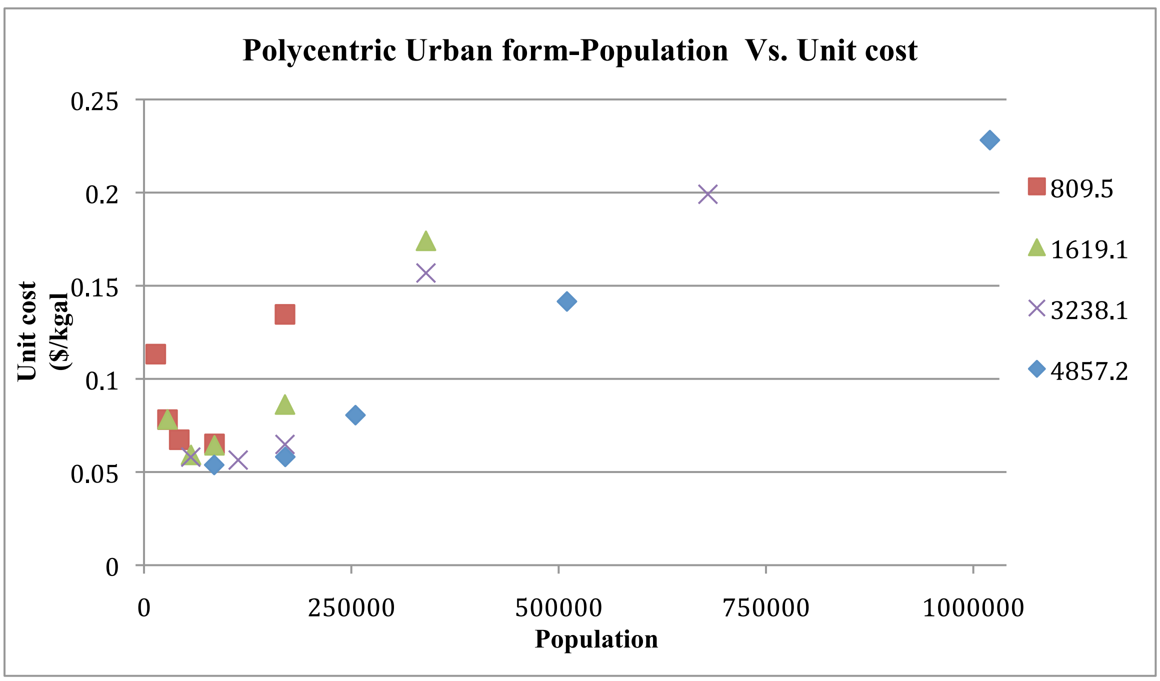


Figure 8. Polycentric urban form- population versus unit cost at different densities

CONCLUSIONS

1) The results show that urban form has a significant impact on the pumping energy cost of water distribution networks, regardless the configuration of the water infrastructure. Among the three urban forms being investigated, for centralized water distribution, sprawling requires the largest amount of pumping energy to serve the same population, being 35% and 46 % higher in pumping costs than the monocentric (5434.5 $/day) and polycentric (4492.9 $/day) urban forms, respectively. When switching from centralized to distributed water networks, the sprawling urban form still showed highest pumping costs, with its 2656.9 $/day, followed by polycentric (2008.8 $/day) and monocentric (1559.0 $/day) urban forms. In the ideal situation, the optimum efficiency could be achieved when the land use planning of an urban area integrates with the water network efficiency.

2) For the size of the urban area being simulated, centralized water distribution networks are 55.3% more energy consuming than distributed water networks, in terms of pumping costs per day. The sprawling, monocentric and polycentric urban forms showed pumping costs reductions of 68%, 71.3% and 55.3% respectively. For the sprawling urban form, changing from centralized to distributed water supply may be an option for efficiency improvement. The operation and maintenance costs, as well as initial capital costs need to be taken into consideration in addition to the pumping cost estimation while planning.

3) An optimum water network service size exists for the same population density.

4) The study of the location of water treatment plant (WTP) on the pumping efficiency shows that siting the WTP at the center of the service area leads to the least pumping

energy demand. Other than the central location, the WTP location that splits the shape of the service area into a symmetrical pattern offers better efficiency than other locations. Ideally, the traditional way of setting up WTP's closer to the water bodies, may need to be reformed, to ensure energy and cost savings.

5) With the increase in number of distributed WTP's allocated for the theoretical city, a declining trend in pumping costs was observed for each of the urban forms. But additional external pumping costs would have to be considered if the source is not locally available.

6) Elevated water networks for both types of water distribution show that elevated water source reduces the pumping head requirements. Centralized water networks showed a 20%, 44%, and 37 % while distributed water network showed a 27.5%, 56% and 12.7% reduction in pumping costs for sprawling, monocentric and polycentric urban forms, respectively. This draws attention to the need to consider the impact of geography on urban forms and the corresponding water distribution layout, too.

FUTURE RESEARCH

The two types of water distribution networks studied in this research- centralized and distributed have their own advantages and limitations while applying to an urban setup. But this study highlighted the need to consider the higher pumping cost savings that can be achieved when distributed water networks are applied to the theoretical city, even despite the initial high capital investments and operation and maintenance costs over centralized water networks. Further studies need to be carried out to prove the impact of urban form and population density on water distribution networks for a real time city.

The application of the results developed need to be applied to a real-time city in order to support the theoretical city's results and to further study the impact of geography, and population density on the water distribution networks. Since a uniform elevation was given to the theoretical city, study on the impact of different elevations on the city would help clearly understand geographical impacts on water networks. Also, the impact of population density on water networks size was studied only for centralized water distribution networks; this should be extended to study distributed water networks and also for further increased population densities. This would help analyze the pattern obtained at higher population densities for an urban setup.

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