Middle States Geographer, 2007, 40:133-141

SPATIAL ANALYSIS OF HOUSEHOLD WATER SUPPLY AND DEMAND IN A DISTRIBUTED GEOGRAPHIC NETWORK IN THE TOWNS OF AMHERST AND CLARENCE, NEW YORK

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ABSTRACT: *Spatial analysis of household water supply capacity and demand was conducted for the towns of Amherst and Clarence, New York. Spatial network models were constructed in Geography Information Systems (GIS) for simulations. Baseline data of household water consumption per person per day, population distribution, and transportation capacity of water main utility lines was collected for the model simulation. The results indicated that as the network extended eastward, southeast part of the Amherst and three of the four sub-regions in the Town of Clarence encountered the discrepancy of supply capacity in meeting the accumulated household water demand.*

Keywords: *Geographic Information Systems, Spatial analysis, Network models, Household water demand*

INTRODUCTION

Household or drinking water supply in urban and suburban regions is one of the key issues of sustainable economic development. The sustainability was presented by Conestoga-Rovers and Associates (CRA) Institute of Education and Training Services as "Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs." (CRA, 2006) Many of the urban infrastructures, such as water mains, streets, sewer lines, were planned and constructed based on the population distribution and economic development at the time of establishment. Consequently, the infrastructures may encounter stress or potential stress as the impact of spatial patterns of population distribution and economic development changes with time.

This study analyzed the impact of current water supply capacity and the house hold demand on a water supply infrastructure in the Towns of Amherst and Clarence, New York. The population distribution, and engineering specification of average per person per day household water consumption, and the water main pipeline network infrastructure were the baseline data to model and simulate spatially the distributed demand in this study. The study was applied in two suburban towns in Western New York that encountered repaid economic development and population growth in the region during last ten years (Amherst Industrial Development Agency, 2005).

Both the Towns of Amherst and Clarence are located in northern Erie County (Figure 1). The area of the former is 53.2 square miles, and that of the latter is 53.5 square miles. According the US Census survey of 2000, the population of Amherst is 116,510 and that of Clarence is 26,123. Therefore, the population density of Amherst is approximately 2,190 people per square mile. By contrast, the population density of Clarence is 488 people per square mile. The water main system in the Town of Amherst is lease managed by the Erie County Water Authority; and that of the Town of Clarence is managed by the town itself, although bulk supply is obtained from the Erie County Water Authority. The water supply of two towns is drawn from Lake Erie through an Erie County Water Authority treatment plant that is located in the Town of Tonawanda, west of the Town of Amherst. The treated water is then pumped to water storage tanks in the two towns for household use. From a water pipeline infrastructure development point of view, the Town of Clarence

water mains are the extension of the water main system from the Town of Amherst.

The Town of Amherst is divided into six different water districts, excluding the Village of Williamsville. Williamsville manages it own water system separately from Amherst and the Erie County Water Authority. The water main system of the town consists of 493 miles of pipeline and two elevated water storage tanks. The Town of Clarence is divided into three different water districts. The water main system of the town consists of 211 miles of pipeline, one elevated water storage tank, and one pump station.

Population in both towns has significantly and consistently increased since 1950s, in particular, since the State University of New York at Buffalo opened its north campus in the Town of Amherst. Economic development intensified the population growth, suburbanization, and urban sprawl in this region. Consequently, it imposes high pressure and demand on its water supply infrastructure.

The U.S. Environmental Protection Agency (EPA, 2002) stated "As our economy and population grow, we must periodically take a good look at the challenges ahead and reassess our nation's need for infrastructure to ensure clean and safe water." The American Water Works Association reported in 2001 that approximately 54,000 water systems, national wide, provide water to roughly 250 million people who live in the urban and suburban regions. The report discussed in detail the affect that the population change has had on water systems over the course of time (Cromwell et al., 2001).

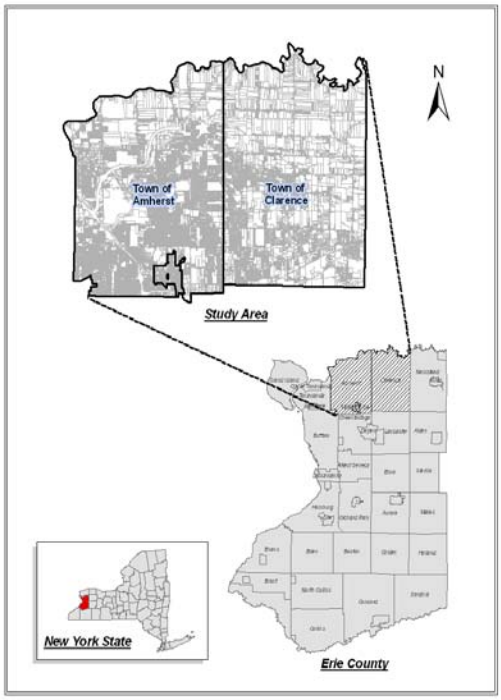

Figure 1. The study area.

Page (2001) indicated that the adequate infrastructure for a potable water supply is a key issue to limit or promote economic growth. Burns and Kenney (2005) studied the development patterns and water infrastructure of the City of Phoenix. They recognized that entire urban infrastructure is experiencing a significant decline in service due to a variety of factors including urban intensification and uneven demand.

The objective of this study is to analyze and visualize the impact of the household water demand, based on population distribution, to a water main network system in supplying the needs. U.S. Census block population data was used to calculate population distributions. The utility network analyst extension in ArcGIS was applied to model and simulate both the demand accumulations and the transportation capacity.

The second objective of this research is to apply spatial network modeling methodology in GIS to guide the regional development practices. Goodchild and Haining (2004) stated the importance of applications of GIS modeling and spatial statistical analysis. "Although GIS and spatial data analysis started out as two more or less separate areas of research and application, they have grown closer over time." As GIS is being applied to various aspects in our society, the relationship between spatial data analysis and GIS becomes more entrenched. This research provides a spatially enabled and detail oriented design and upgrading tool of water main pipelines in a region. This approach departs from the traditional methods of estimating the needs based on the forecasting of economic development and total population data.

METHODS AND APPROACHES

Data Collection

Six spatial and non-spatial datasets were collected for this analysis: tabular data of U.S. Census population by geographic area of block groups; U.S. Census block group shapefiles; water main pipeline of the two towns in shapefile format; pipe junction data in shapefile format; parcel boundary files for the Towns of Amherst and Clarence that depict geographic locations of household water consumptions; and the standard average daily consumption of household water

supply per person from published water works and water utility engineering literature.

The water pipeline data and pipe junction data was obtained from CRA of Buffalo, New York. The water main pipeline data set was originally created by the Erie County Water Authority in the late 1980's, and subsequently updated to the current time. Attribute data included with the pipeline shapefile were: pipe diameter, maximum pipe discharge and pipe length. Attribute data included with the pipe junctions were junction ID numbers and junction discharges.

The average per gallon consumption of water per day per person was obtained from the manual of the Advanced Water Distribution Modeling and Management (Cesario, 1995). The manual is considered as a standard guideline book for hydraulic engineering works by the American Association of Water Works. The standard consumption per person per day used in this study is an average amount from all the different residential types listed by the research. The average amount is 105.5 gallons per person per day.

Data Preparation and Analysis

A unique ID number was established in both the U.S. Census Population Survey attribute table and the attribute table of the block group shapefile. This was accomplished by using a standard naming convention that was established in the Census block group. The tabular data was then joined to the shapefile. After the datasets were joined, two additional fields were created in the attribute table in order to calculate the demand of household water supply by geographic areas of block groups. The standard of average per person daily water consumption, 105.5 gallons, was input into the first column. The total block group water consumption was calculated in the second column. The total block group water demand was determined by multiplying the total population of each block group by the per person average daily water consumption.

The water main pipeline network and pipeline junction data was duplicated for two types of network model simulations, namely "water supply capacity" and "water demand". The former is a distributed magnitude from the sources to the end user communities, and the latter is an accumulative magnitude, from the end user communities to the sources. Recognizing several major factors that contribute to water pipeline capacity, a working assumption was made that pressure, flow velocity, pressure-head loss and pipeline material were all constant across the entire system. This is the general assumption that is made by most regional scale engineering modeling of water main pipeline networks. Based on this assumption, the maximum pipeline discharge capacity is a direct function of the diameter width of the pipelines.

The spatial network model of water main pipeline demand was overlaid on the Census block group feature class. A demand field was created in the attribute tables of both water main network feature class and Census block groups. The pipeline network was classified into major transportation mains, primary distribution mains, and distribution mains to the block group communities. In many cases, several distribution mains feed into one block group in the study area. In order to calculate accurate household water demands, parcel level land use and land ownership distribution data of the two towns was overlaid to each of the Census block groups to generate the weights of detailed population distribution and house hold water request for each of the distributional water mains within each block group. The computed water demand through spatial join of population distribution and distributional water mains to the communities were transferred and stored in the water main pipeline spatial network model as the initial values of model simulation.

A distributed geometric network model was established in a geodatabase in ArcGIS for water demand simulation (Figure 2). The demand attribute in the pipeline model was established as the weight within the network and the pipe junction associated with the water treatment plant was established as the sink location within the network model.

Applying the utility network analyst in ArcGIS, the upstream demand accumulation was simulated on the pipeline network at various points throughout the system to determine total demand accumulated for each of the locations of the entire network. The household water demand map layer was overlaid on the water supply capacity map layer to calculate the spatial patterns of the discrepancies.

RESULTS

The total maximum supply for the primary transportation main entering the Town of Amherst, from the water treatment plant at the Town of Tonawanda, is 29 million gallons per day (Erie County Water Authority, 2006). The total accumulated household water demand from the communities in the two towns, as simulated in this study, is 15.1 million gallons per day (Figure 2). In general, the current usage of the capacity is fifty-one percent at the entrance of this distribution network.

However, detailed examinations of the house hold water supply in a more localized scale on the network model yielded varied results (Figure 3).

The simulation results of Northwest Amherst are shown in Figure 4. There is a sufficient water supply to meet the demand in this area. At the point indicated on the map, the demand is approximately 6.2 million gallons per day. At the same location there is a 42 inch transportation line that has a maximum discharge value of 12 million gallons per day. The demand at this locality is up to 51% of the potential supply capacity at this time.

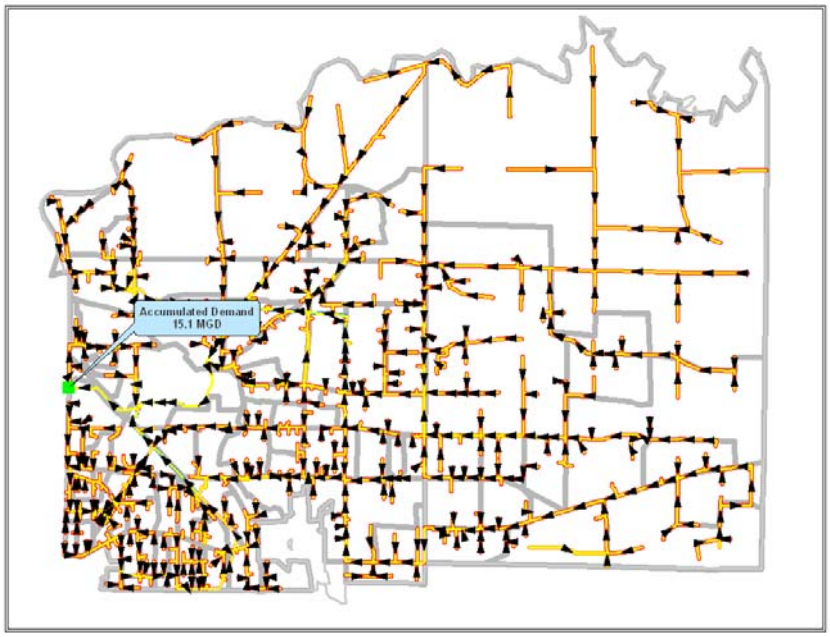

Figure 2. The general spatial pattern of the household water demand in the two towns' region. (The arrows point the directions of accumulations of household water demand)

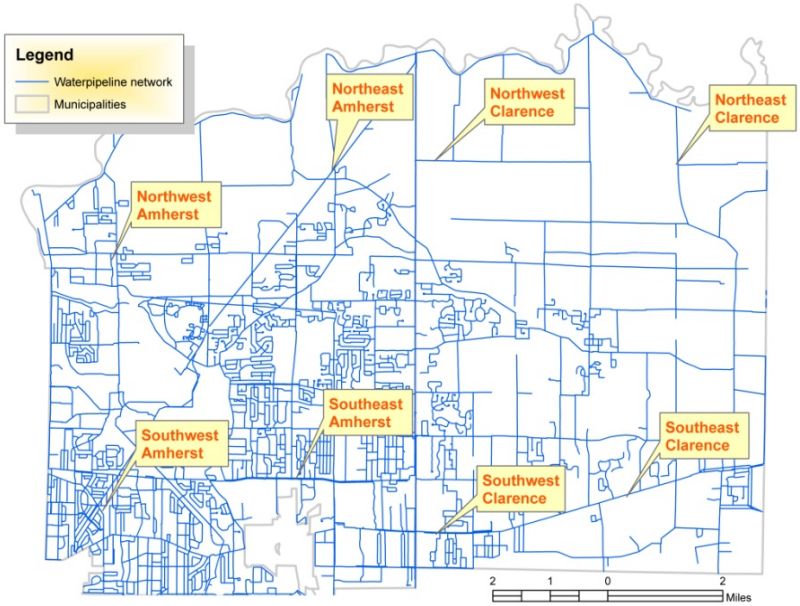

Figure 3. Water pipeline network in two towns and the locations of detail study areas.

The simulation results of Southwest Amherst are shown in Figure 5. It appears that there is sufficient water supply to meet the demand in this region. The demand is approximately 7.3 million gallons per day at the point indicated in the map. At the same locality, there is a 36 inch transportation line that has a maximum discharge value of 8.8 million gallons per day. The current household water demand in this region is approximately 83% of the potential supply capacity.

The simulated results of Northeast Amherst are shown in Figure 6. The results indicate that there is sufficient water supply to meet the demand in this area. The accumulated demand at the point indicated on the map is approximately 4.6 million gallons per day. The maximum transportation capacity at this location is 9 million gallons per day. The model

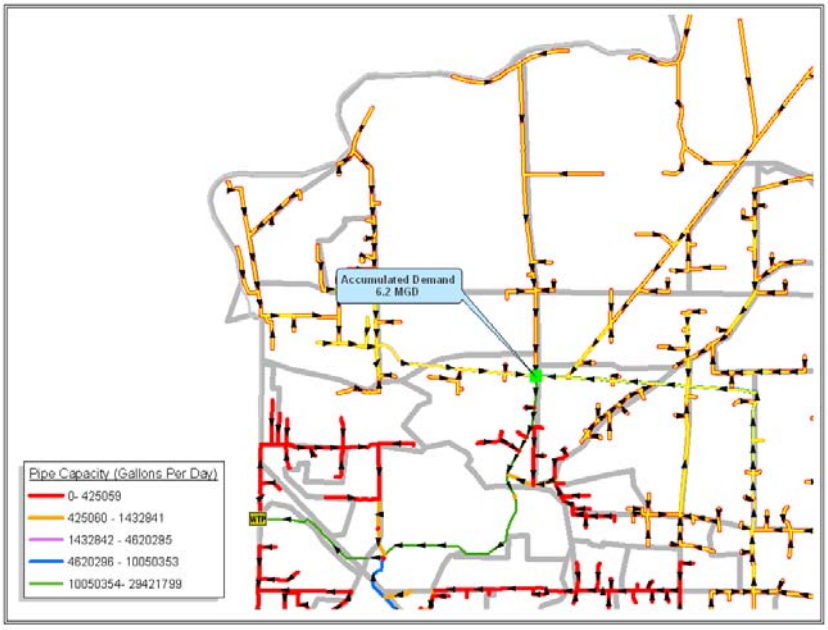

Figure 4. Spatial simulation of household water demand in Northwest Amherst.

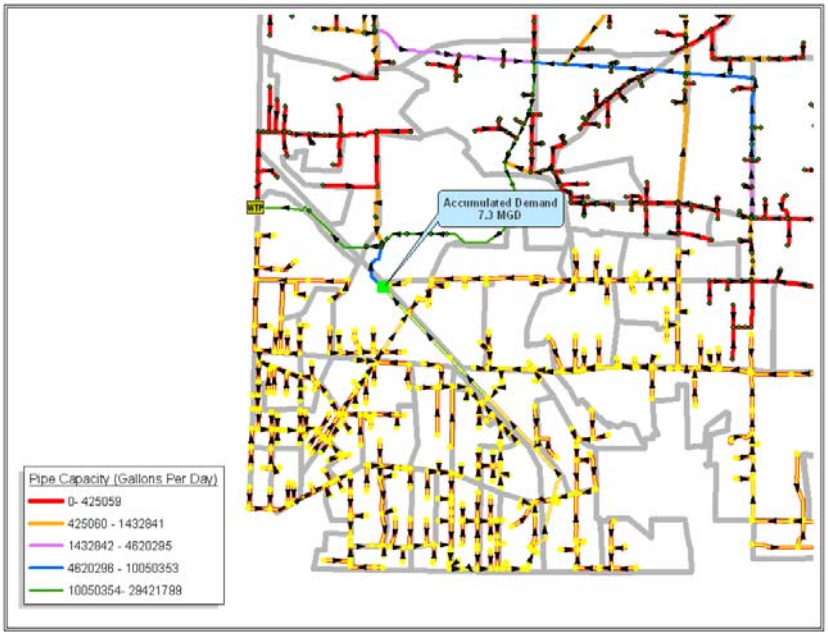

Figure 5. Spatial simulation of household water demand in Southwest Amherst.

predicted demand in this region is approximately 51% of the potential supply capacity.

Results of simulations in Southeast Amherst are shown in Figure 7. The results indicate that insufficient household water supply exists in this region. The accumulated household water demand in this region is 2 million gallons per day. In the meantime, the transportation capacity at the same locality is 0.5 million gallons per day with a 16 inch transportation line. Additional point simulations were conducted in this region also showed discrepancies of supply capacity to the accumulated demand. The simulated demand in this region has exceeded the current supply capacity for three times. The water main transportation network in this region encounters high pressure. Consequently, high pressure of demand may cause frequent pipeline ruptures.

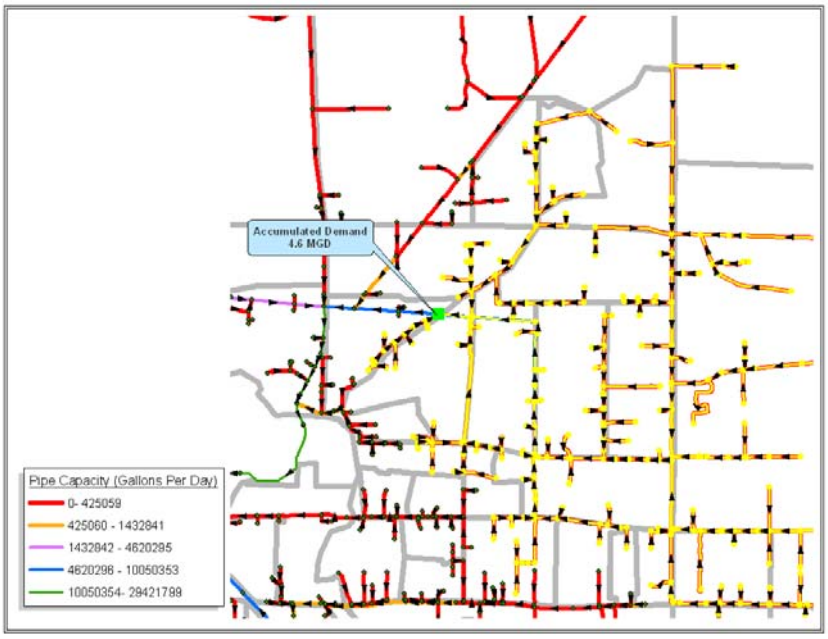

Figure 6. Spatial simulation of household water demand in Northeast Amherst.

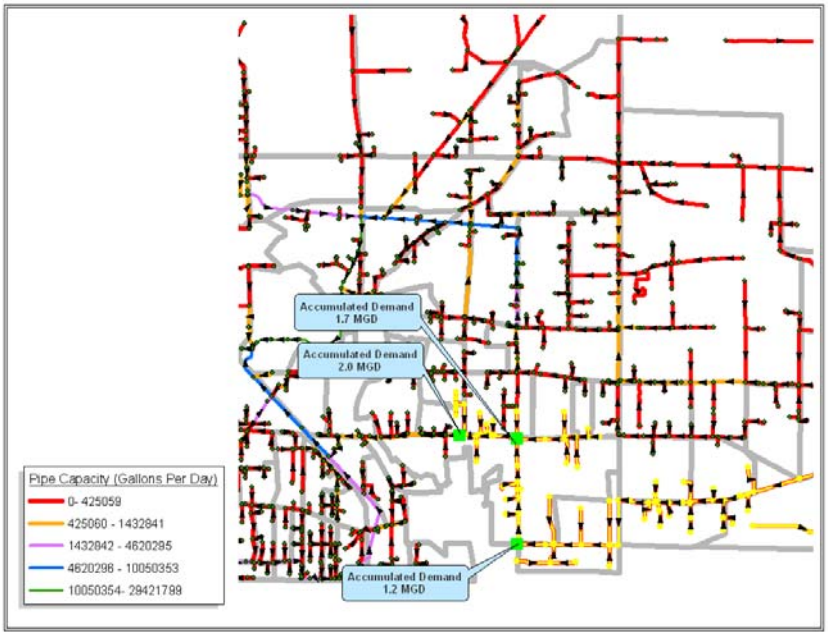

Figure 7. Spatial simulation of household water demand in Southeast Amherst.

Results of simulated demands in Northwest Clarence are shown in Figure 8. It indicated that there is an insufficient water supply in meeting the demand. Two points were examined in details. The first point shows a demand of 1.2 million gallons per day. However, the maximum current transportation capacity is 0.85 million gallons per day. The demand is 150% of the supply capacity. The second point shows a demand of 0.5 million gallons per day, but the maximum current discharge capacity is 0.10 million gallons per day with a 10 inch transporting line. The demand is 500% of that of the supply capacity.

The simulated results of Southwest Clarence are shown in Figure 9. The demand and supply are in general balanced in this region. For instance, the

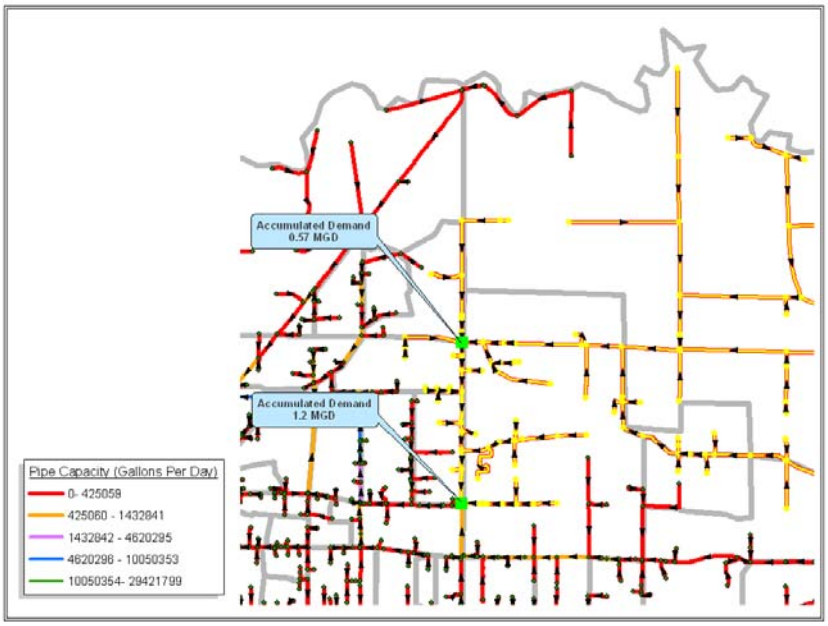

Figure 8. Spatial simulation of household water demand in Northwest Clarence.

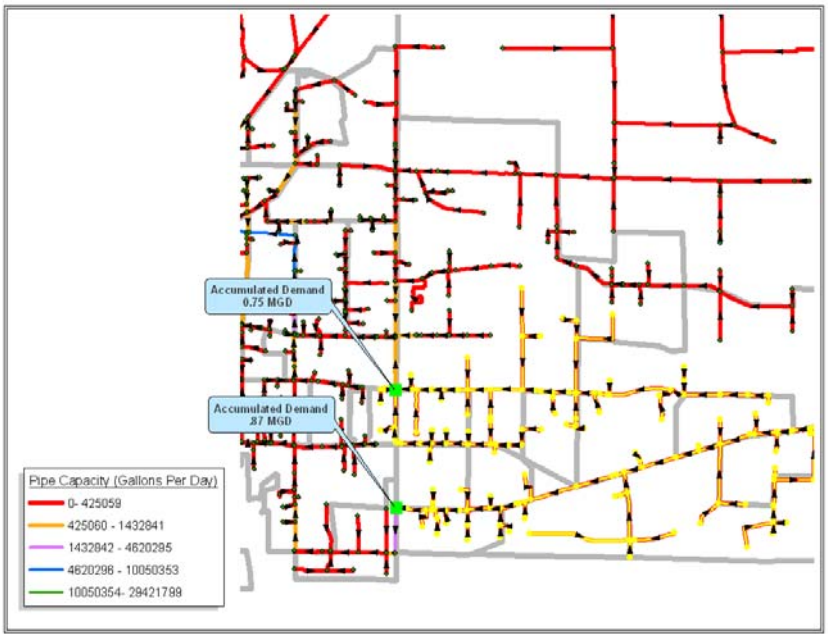

Figure 9. Spatial simulation of household water demand in Southwest Clarence.

demand of the first point is 0.75 million gallons per day, and that of the second survey point is 0.87 million gallons per day. The delivery capacity of the former is 0.85 million gallons per day, and that of the latter is 1.7 million gallons per day.

Simulation results of Northeast Clarence are shown in Figure 10. The results indicated that insufficient of water supply exists. The demand at the survey point is 0.30 million gallons per day, but the transportation capacity of the pipelines is only 0.13 million gallons per day as an 8 inch transportation line was installed for these newly developed communities. The demand is more than 200% of the current supply capacity.

Simulated results of Southeast Clarence are shown in Figure 11. Again, insufficient of supply capacity exists in this region. For instance, the demand at the point on the map is 0.47 million

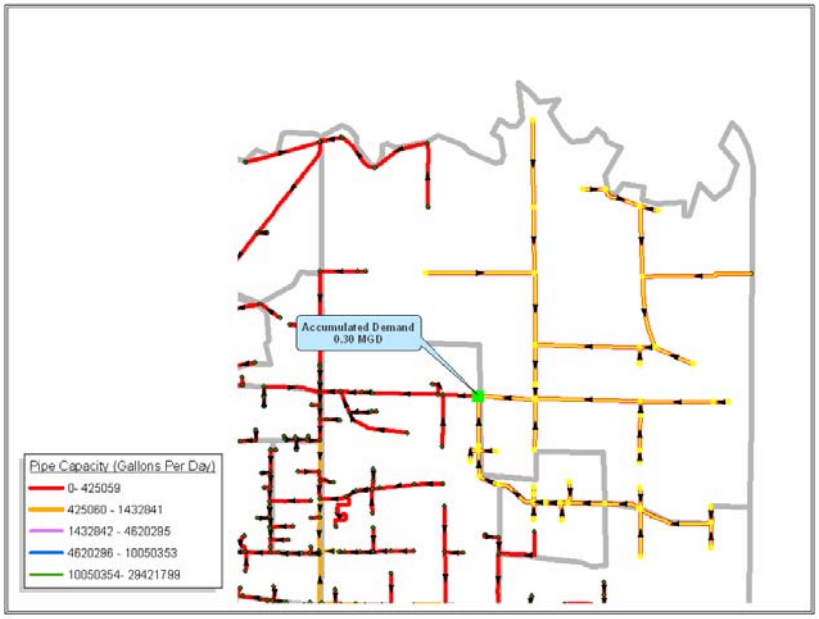

Figure 10. Spatial simulation of household water demand in Northeast Clarence.

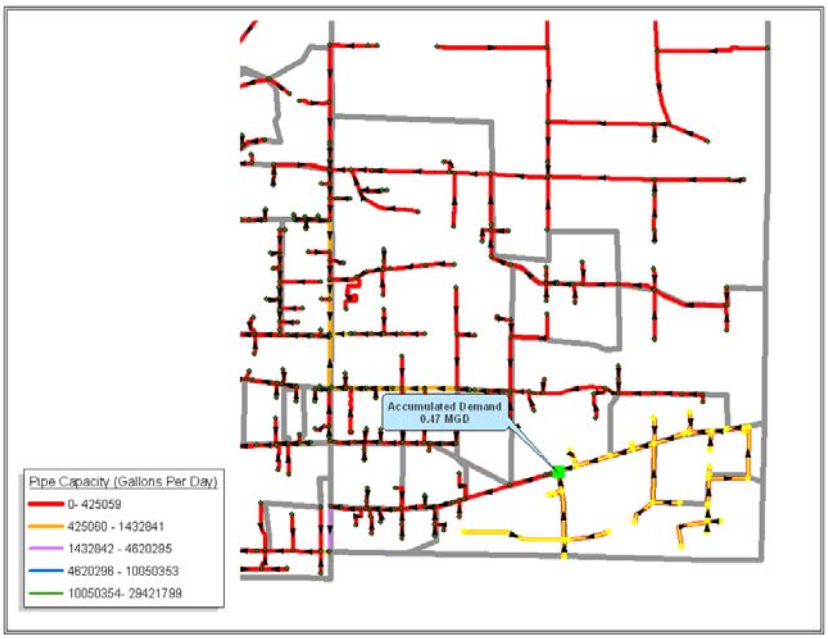

Figure 11. Spatial simulation of household water demand in Southeast Clarence.

gallons per day. However, the supply discharge capacity is 0.30 million gallons per day. The model simulation predicted that the demand is 150% of the supply capacity.

DISCUSSION AND CONCLUSIONS

Half of the eight geographical surveying areas appears encountering insufficient balance of household water supply and demand. Three of the four unbalanced regions are located in the Town of Clarence that is in the east part of the study area. Among these regions, the highest discrepancy occurs in the southeast part of Amherst. The demand exceeded the supply capacity from 300% to more than 400%. The second highest occurs in Northeast Clarence that exceeds 100% of their current supply capacity.

The results of this study suggest that the municipal water supply system developed in the Town of Amherst was not planned to serve the population growth and urbanization in the Town of Clarence. Town of Clarence previously was a rural community. However, continued urban sprawl and industrial development eastward from Amherst to Clarence intensified the household water requirements. Consequently, the continued extension of water mains to serve additional customers would create additional burden to a system and pressure head drop of the pipeline system. The highest discrepancy occurs in Southeast Amherst possibly because that locality on one hand is the major water supply channel to the Town of Clarence. On the other hand, Southeast Amherst is also one of the most densely populated regions in the town. Meanwhile, the Northeast Clarence is located at the tail part of this water main distribution system. The pipeline pressure head drop may contribute a great percentage of the deficiency in this area. Future studies of this water distribution system need to identify solutions of unbalances, such as installing larger sized transportation lines, construction of pump stations and additional water storage tanks to increase the regional pressure heads.

In summary this study modeled and simulated the accumulated household water demand in relation to the hydraulic discharge capabilities of a distributional water main pipeline network. It attempts to identify the spatial pattern of discrepancies between the supply capacity and the accumulated demands on the water main utility network. The general approach of this study can also be applied for other types of utility network analysis, such as power distribution networks. This approach facilitates sustainable development in the municipalities across the United States.

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