MICROPOLIS: A VIRTUAL CITY FOR WATER DISTRIBUTION SYSTEM RESEARCH APPLICATIONS

A Senior Scholars Thesis

by

JACOB MANUEL TORRES

Submitted to the Office of Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

April 2006

Major: Civil Engineering

MICROPOLIS: A VIRTUAL CITY FOR WATER DISTRIBUTION SYSTEM RESEARCH APPLICATIONS

A Senior Scholars Thesis

by

JACOB MANUEL TORRES

Submitted to the Office of Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

Approved by:

Research Advisor:	Kelly Brumbelow
Associate Dean for Undergraduate Research:	Robert C. Webb

April 2006

Major: Civil Engineering

ABSTRACT

Micropolis: A Virtual City for Water Distribution System Research Applications (April 2006)

Jacob M. Torres
Zachry Department of Civil Engineering
Texas A&M University

Research Advisor: Dr. Kelly Brumbelow
Zachry Department of Civil Engineering

For security reasons, cities keep their water distribution system data confidential. This data includes geographic layout of pipes, tanks, pumps, wells, buildings, and demands. While the secrecy of water system data is crucial, it poses a difficulty for research on water distribution systems as results can not be publicized. Therefore, a library of virtual water distribution systems can be an important research tool for comparative development of many analytical methods. A “virtual city” has been developed, including a comprehensive water distribution system, as a first entry into such a library. “Micropolis” is a virtual city of 5000 residents fully described in both geographic information systems (GIS) and EPANet hydraulic model frameworks. To simulate realism of infrastructure, a developmental timeline spanning 130 years was described, and this timeline is manifested in items such as pipe material, diameter, and topology. Examples of using the virtual city for simulations of contaminant spread are presented, and future applications will include fire flow and water auditing. The data digital files describing Micropolis are available from the authors for others’ use. It is hoped that other virtual cities will follow for the use of the research community.

To my mother, the strongest woman I know.

ACKNOWLEDGMENTS

I would like to extend a special thank you to my research advisor, Dr. Kelly Brumbelow, for accepting me into his research group and allowing me to participate in such a meaningful research project. Thanks also to my research partner and friend, Elizabeth Bristow, for her patience and guidance throughout various stages of this research. A warm thanks is also extended to Dr. Roger Smith, my 2004 undergraduate research scholarship supporting chair.

Finally, I would also like to thank the entire faculty and staff of the Zachry Department of Civil Engineering for their successful efforts in fostering the undergraduate research environment. Their support and encouragement for undergraduate research and continuing through graduate studies is greatly appreciated.

NOMENCLATURE

WDS	Water Distribution System
GIS	Geographic Information System
HydroGEN	Hydraulic Model Generator
WTP	Water Treatment Plant
WWTP	Waste Water Treatment Plant

TABLE OF CONTENTS

Page

CHAPTER

LIST OF FIGURES

CHAPTER I

INTRODUCTION: THE IMPORTANCE OF CONTAMINATION EVENT MODELING

History has proven that city water distributions systems (WDS) are far from failsafe. Case studies have also revealed WDS vulnerabilities to contamination. In an age where terrorist-proof systems are becoming key factors in engineering design, it is also important to look at how this factors into a city's water distribution system. For evident reasons, cities keep their water data confidential. This data can include detailed information on a city's water distribution system, such as geographic layouts of pipe, tanks, wells, and pump stations. Other confidential information can include building blueprints and their associated water demands. This class of information is considered sensitive and is therefore made unavailable to the public. For this reason, the development of a virtual city is necessary for an accurate representation of true city characteristics. Micropolis is a virtual city that has been created to reflect the key features of a true city. It represents a small town of approximately 5000 residents. This virtual city's WDS is capable of being modeled for a contamination event via a hydraulic modeling program. During the simulation, the contaminant spread is closely monitored and the effects for those who depend on the water for daily usage is analyzed. It is hoped that contamination vulnerabilities of the Micropolis water distribution system will be extracted so that actions can be taken for developing effective contamination response procedures and steps for improving the overall system integrity.

This thesis follows the style of *Journal of Water Resources Planning and Management.*

CHAPTER II

RESEARCH OBJECTIVES

This research can be summarized in three phases. Phase 1 requires the application of a Geographic Information System (GIS) needed for creating Micropolis. The second phase involves the transfer of Micropolis into a hydraulic modeling program for contamination simulation. Finally, the third phase involves the collection of results and the repeat of Phase 2 for different contamination scenarios. These different contamination scenarios refer to the introduction of different contaminants, the same contaminant at a different location, or adjustment to initial setup conditions for the water distribution system. A figure of this three phase process is provided in Figure 1. Once an acceptable understanding on Micropolis's vulnerability to contamination is determined, intervention procedures can then be proposed. These procedures could include valve and pipe isolation emergency response plans so to minimize detrimental effects on city residents. Further details concerning these phases are discussed in subsequent chapters.

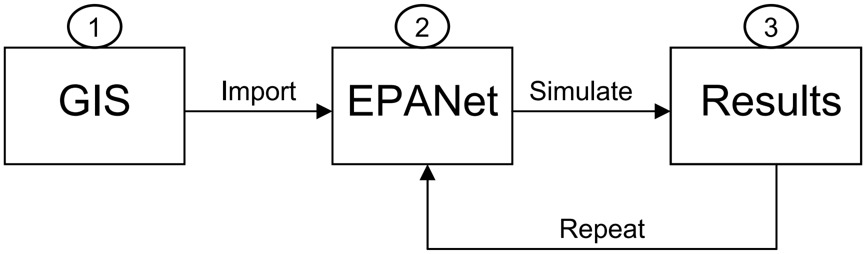


Fig. 1. Research Phases

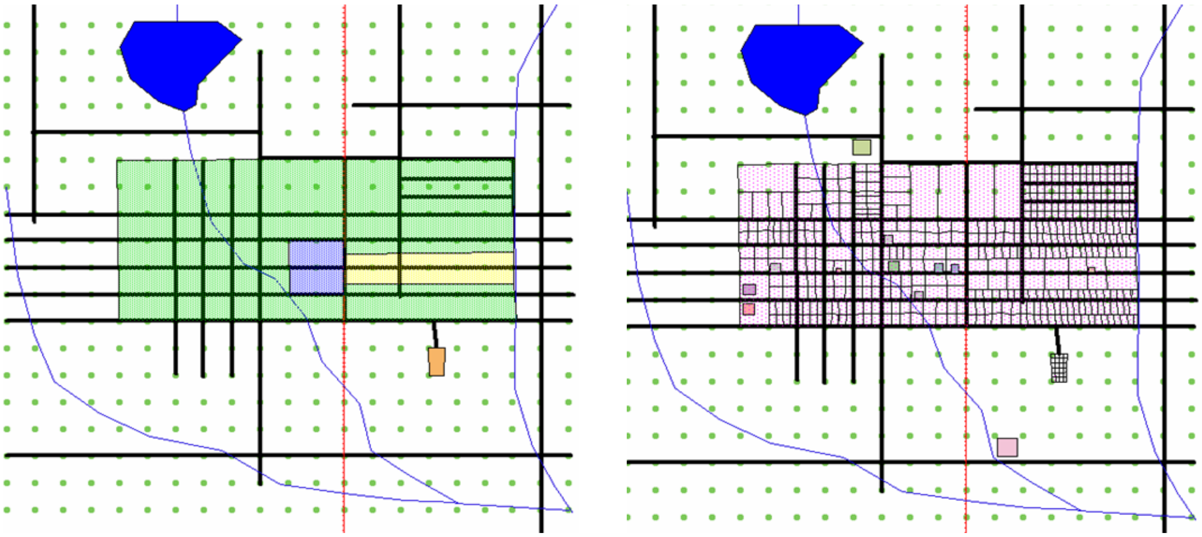
CHAPTER III

PHASE 1 – BUILDING MICROPOLIS

The first phase involves the application of a Geographic Information System (GIS) to create Micropolis from scratch. ArcView 3.2 and ArcMap 9.0 are the GIS tools that were utilized to carry out this process. Knowledge of city planning was needed in the building of Micropolis. This virtual city was developed on a timeline basis to incorporate the attributes of a true city. For example, it was assumed that Micropolis was first settled during the 1850s and continued to expand in time. Another advantage of following a timeline development pattern was the consideration of varying pipe material throughout a city's water distribution system. During the early 1900s most pipes were of cast iron material. Micropolis reflects this behavior in the oldest part of the city (downtown). Pipes installed in Micropolis during the 1950s consisted mainly of asbestos cement pipes, whereas pipes installed during the 1980s were of ductile iron. Varying pipe material means varying pipe roughness factors. This plays an important role when considering hydraulic behavior, as discussed in Phase 2.

An important consideration in the development process was to understand certain imperfections of a true city's water distribution system. Incorporating these imperfections in Micropolis was necessary if the standard of modeling a true city was to be maintained. Incorporating some of these imperfections involved intentional service connection misalignment with water mains and locating fire hydrants contrary to code specifications.

Among the first steps in creating Micropolis entailed the configuration of a distance grid. This grid is indicated in Figure 2 (a) and (b) as equally spaced green dots. These imaginary dots represent distance intervals of 1000 feet. Planning the terrain was the next step. This was accomplished using a GIS. The city's main sources of water supply come from groundwater and a reservoir located just north of the city. The next step involved placement of city roads and setting zone boundaries for identifying industrial, commercial, and residential areas. A layout of this is presented in Figure 2 (a). The black lines represent the roads and the red vertical line represents the railroad track. The green, purple, and the yellow areas represent the residential, commercial, and industrial zones, respectively.



(a) (b)

Fig. 2. Micropolis Layout I: (a) grid, roads, railroad, zones, and (b) property lots and buildings.

Figure 2 (b) depicts numerous adjacent rectangles. These rectangles represent designated property lots. These lot sizes vary according to lot purpose. Some lots are for apartment complexes, while others are for single family residents. Lots for commercial and industrial zones are also included. Some facilities represented in Micropolis include restaurants, schools, post office, churches, and small businesses.

Water mains were obviously included. Water mains are indicated as thick blue lines in Figure 3 (a). It is noted in Figure 3 (a) that water mains are located parallel to main roads, as they are in reality. In addition to water mains, service connections were created to provide water demands to property lots. This is presented in Figure 3 (b). The service connections are indicated as thin blue lines branching off the water mains. Red and green point shapefiles represent fire hydrants and valves, respectively.

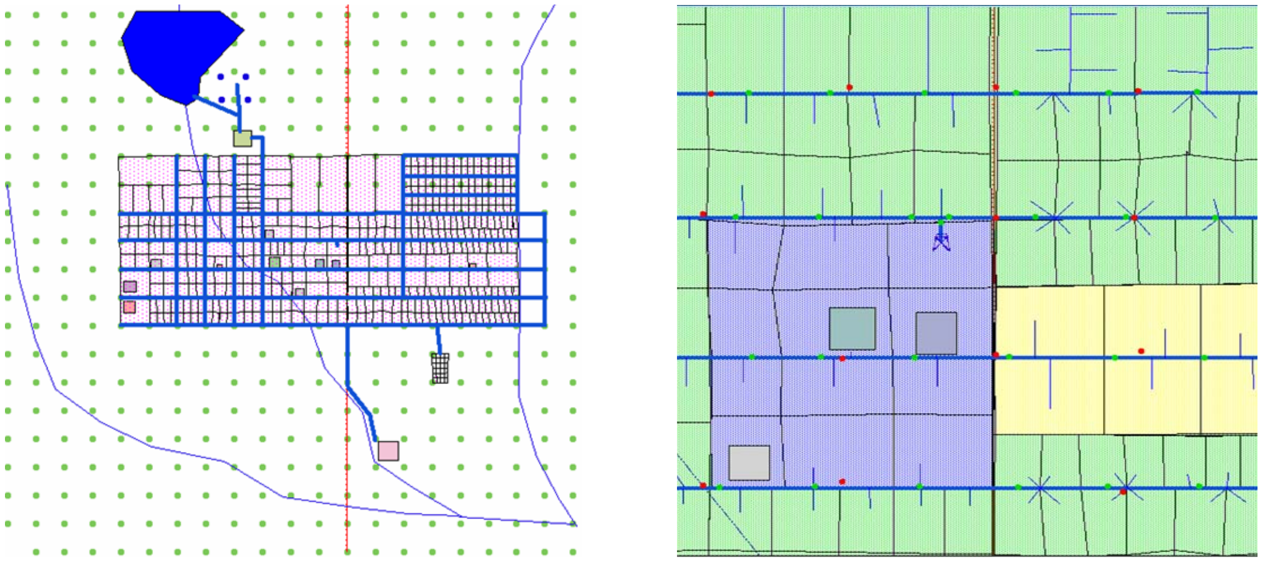

(a) (b)

Fig. 3. Micropolis layout II: (a) water mains and (b) valves, hydrants, and service connections.

Table 1. Pipe and Service Connection Characteristics

Pipe Material	Year Installed	Roughness (in)	Diameter (in)	(ε / D)[a]	friction factor
Cast Iron	1910	0.009843	2	0.004921	0.0300
			4	0.002461	0.0240
			6	0.001640	0.0220
Asbestos Cement	1950	0.004800	4	0.001200	0.0200
(C = 140)[b]			6	0.000800	0.0185
			8	0.000600	0.0175
Ductile Iron	1980	0.004800	4	0.001200	0.0200
(C = 140)[c]			6	0.000800	0.0185
			8	0.000600	0.0175
			12	0.000400	0.0160
Copper	1910	0.000060	¾	0.000080	0.0115
new			1	0.000060	0.0110
			2	0.000030	0.0095
			4	0.000015	0.0085
Plastic	1980	0.000039	¾	0.000052	0.0105
			2	0.000020	0.0087

[a] (fully turbulent flow is assumed).

[b] (Wurbs and James. 2002).

[c] (www.DIPRA.org).

All pipes have characteristics that need to be included when running a water distribution system contamination simulation. These characteristics include installation years, roughness coefficients, pipe size, and friction factors, as shown in Table 1. For example, the Hazen-Williams coefficient for ductile iron is 140 (Ductile Iron Pipe Research Association 2006) and the Darcy-Weisbach friction factor for cast iron is 0.009843 (Wurbs and James 2002). ArcView 3.2 allows this data to be incorporated through attribute tables.

The next task required the assignment of elevation data to all pipe nodes. This was easily accomplished with the help of ArcView 3.2 by manually inserting elevation point shapefiles and assigning elevation values to these points. Elevation point shapefiles were carefully chosen to reflect high and low elevations for the preexisting Micropolis terrain. For example, low elevation points were assigned for stream and river areas. These elevation points could then be interpolated to obtain an elevation grid for all areas of Micropolis. Figure 4 illustrates the Mircopolis's elevation grid as it exists in a GIS. The legend indicates an elevation range in units of feet.

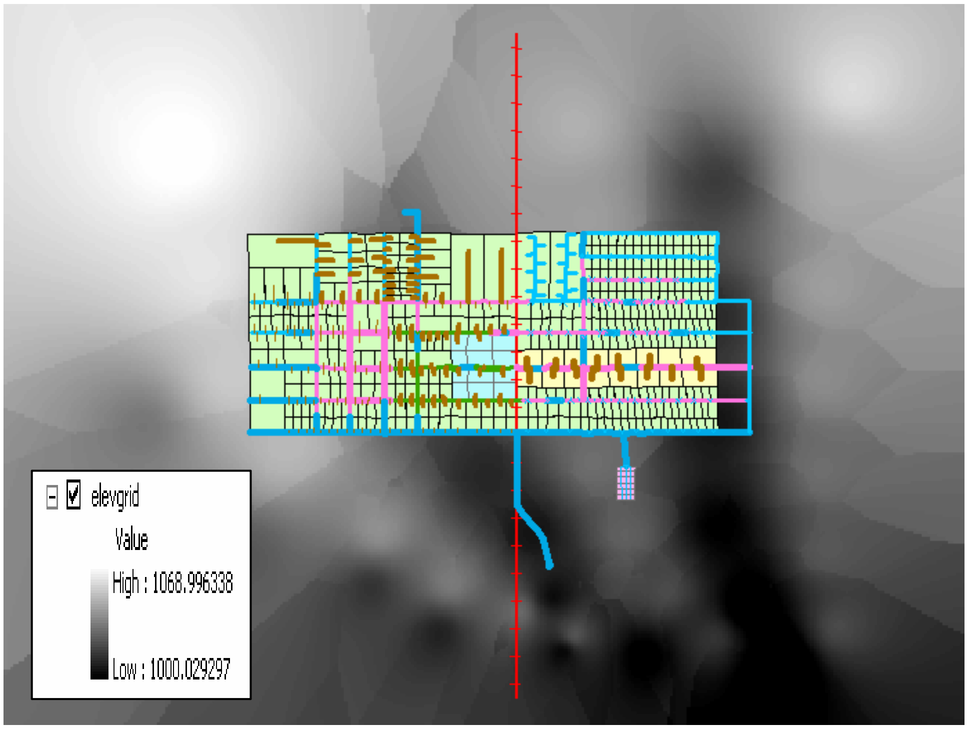
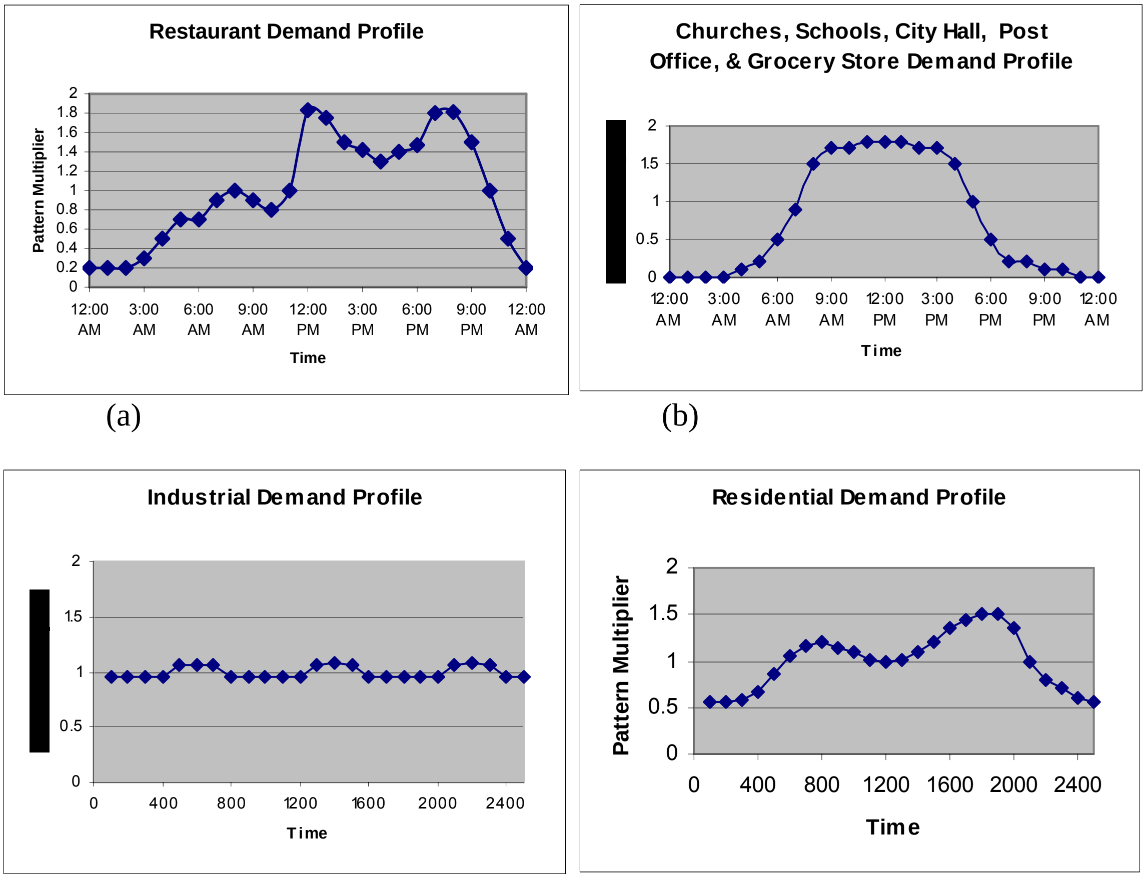


Fig. 4. Elevation Grid

The final step prior to Phase 2 was the assignment of water base demands to all terminal nodes. An important aspect to consider when modeling a real city is base demand variation. For example, water demand for a single family residence is different for demand of a textile factory. In other words, different quantities of water are used at different peak hours of the day. To account for this variation, diurnal curves (demand profiles) were needed to accurately assign base demands for all property lots. These curves were derived in consultation with Haestad Methods *Advanced Water Distribution Modeling and Management* (2003). In Micropolis, the curves considered were residential, industrial, schools, grocery stores, and restaurants. These demand profiles depict the average water demands that are typical of small towns. These profiles are presented in Figure 5 for a 24-hr period. The hydraulic modeling program, EPANet, is capable of taking these curves and assigning them to desired terminal nodes at which a demand can be taken.



(a) (b)

(c) (d)

Fig. 5. Demand profiles for (a) restaurants, (b) churches, schools, grocery stores, (c) industrial zones, and (d) residential zones.

After pipe characteristics, elevations, and base demands were obtained, preparation for transfer of Micropolis into an EPANet framework was initiated. HydroGEN, an ArcView 3.2 extension, was utilized to convert the Micropolis pipe network into a workable input file for the EPANet modeling program. To successfully apply HydroGEN, a pipe network, water demand, and elevation shapefile were required in a GIS. Water sources and pumps are not transferred by HydroGEN, and are therefore added manually in the EPANet program. Once the EPANet input file is imported and opened, the result is the Micropolis water distribution system, as illustrated in Figure 6.

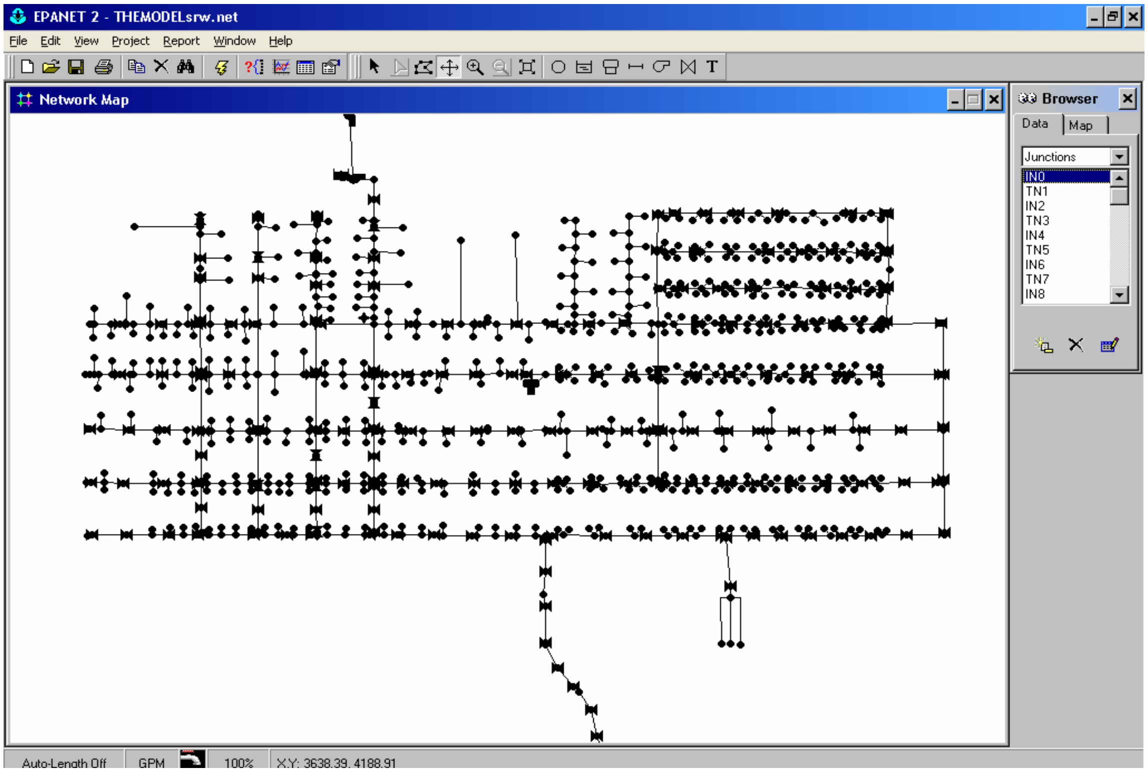


Fig. 6. Micropolis in EPANet

CHAPTER IV

PHASE 2 –MODELING CONTAMINATION EVENTS

Phase 2 involves EPANet applications for running the Micropolis hydraulic and water contamination simulations (Rossman 2000). EPANet is a program provided by the Environmental Protection Agency for simulating hydraulic and water-quality behavior within pressurized pipe networks. A network can consist of pipes, pipe junctions, pumps, valves and storage tanks or reservoirs. Micropolis contains a total of 1500 junction nodes that are capable of being tested for contamination simulation. Examples of three contamination scenarios are explained. Consider a chemical contaminant to be inserted at the indicated intrusion point in Figure 7.

The first step in running this simulation involves defining the contaminant. Figure 8 presents EPANet prompt boxes for defining a contaminant. For the first contamination scenario, a hypothetical first order reaction decay contaminant will be pumped against pressure at the indicated insertion point. This contaminant will enter the system at a continuous initial concentration and the simulation will run for an arbitrarily chosen period of five days.

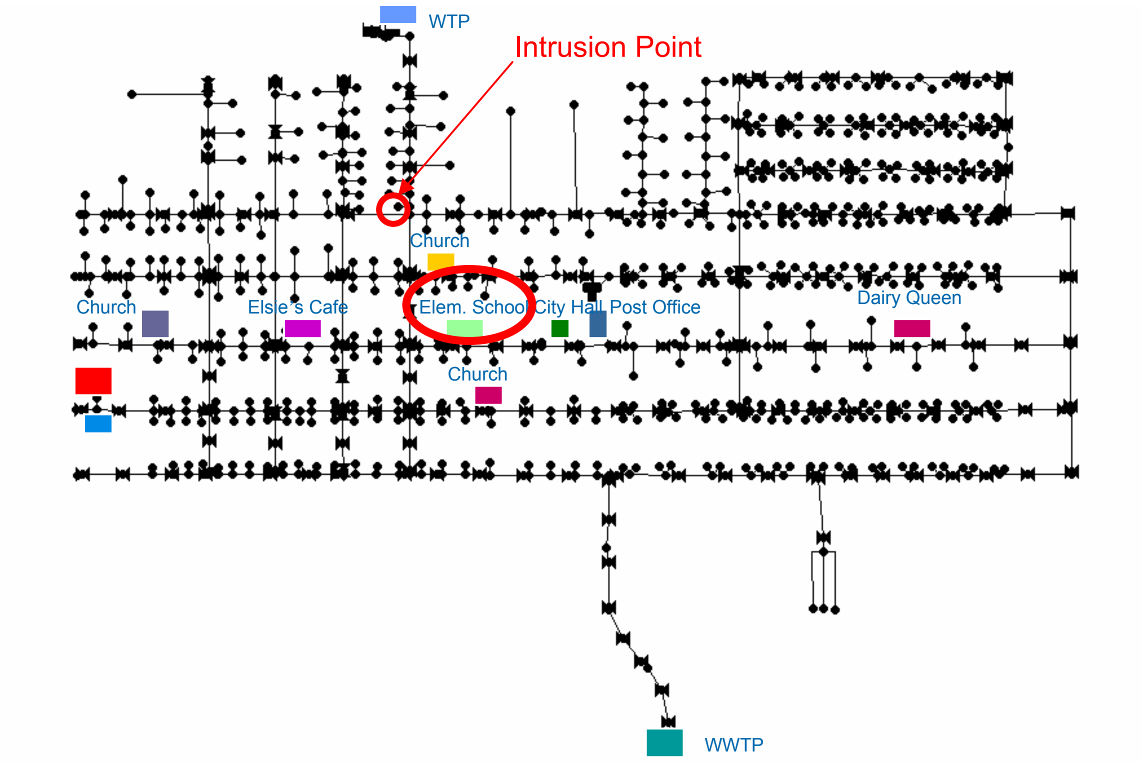
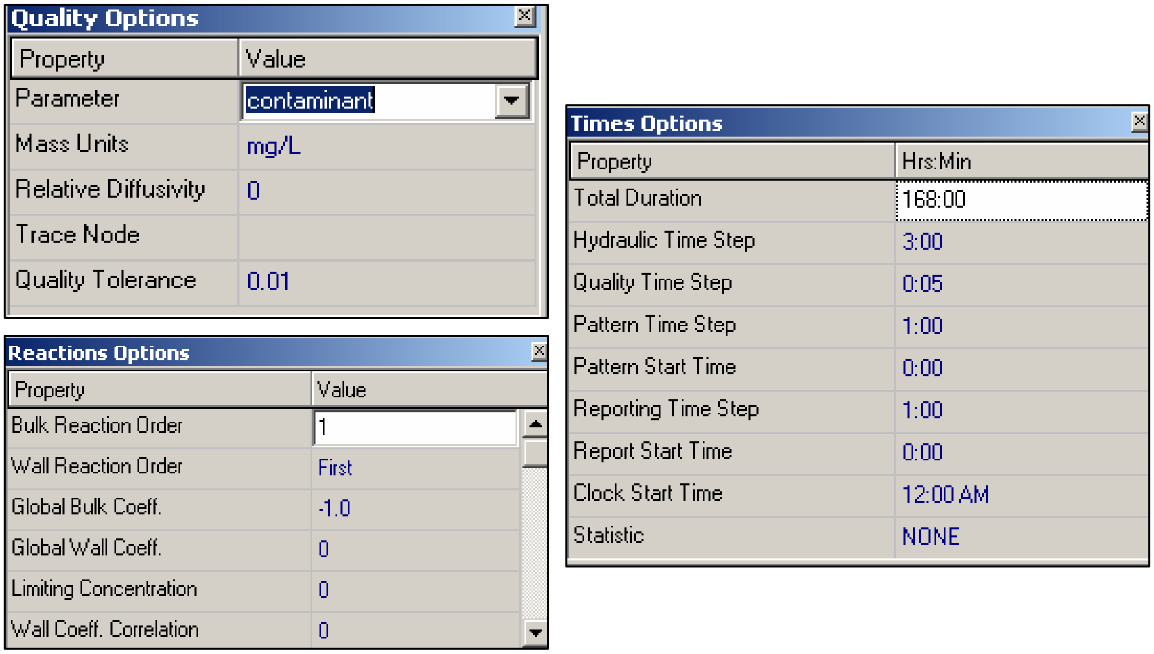


Fig. 7. Contamination Scenario 1



Quality Options

Property	Value
Parameter	contaminant
Mass Units	mg/L
Relative Diffusivity	0
Trace Node	
Quality Tolerance	0.01

Reactions Options

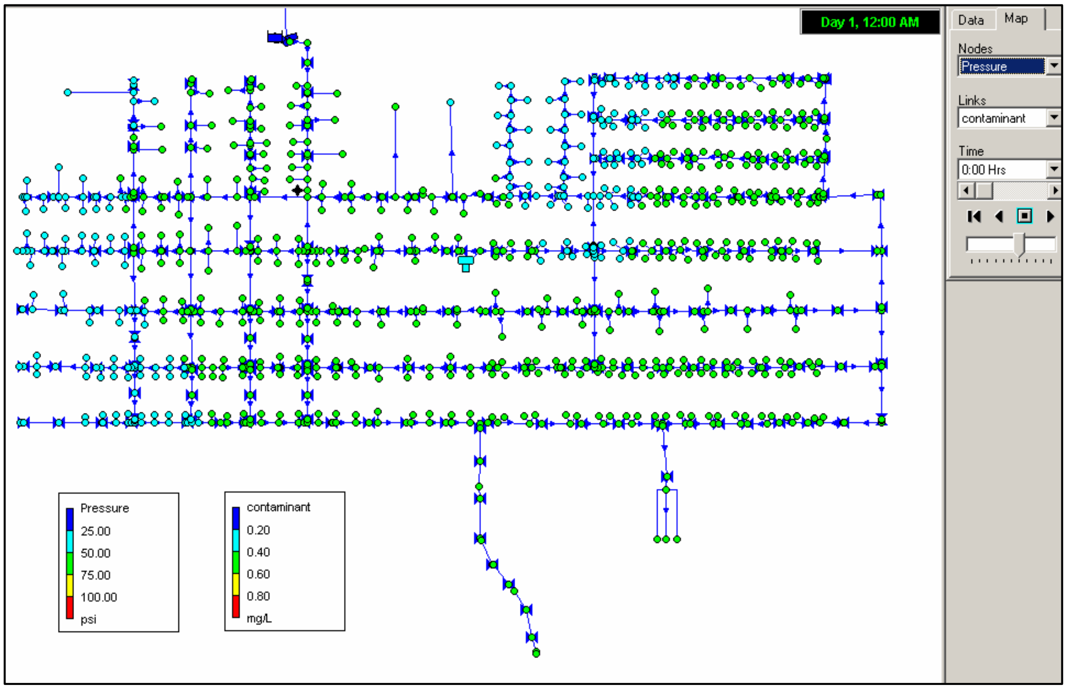
Property	Value
Bulk Reaction Order	1
Wall Reaction Order	First
Global Bulk Coeff.	-1.0
Global Wall Coeff.	0
Limiting Concentration	0
Wall Coeff. Correlation	0

Times Options

Property	Hrs:Min
Total Duration	168:00
Hydraulic Time Step	3:00
Quality Time Step	0:05
Pattern Time Step	1:00
Pattern Start Time	0:00
Reporting Time Step	1:00
Report Start Time	0:00
Clock Start Time	12:00 AM
Statistic	NONE

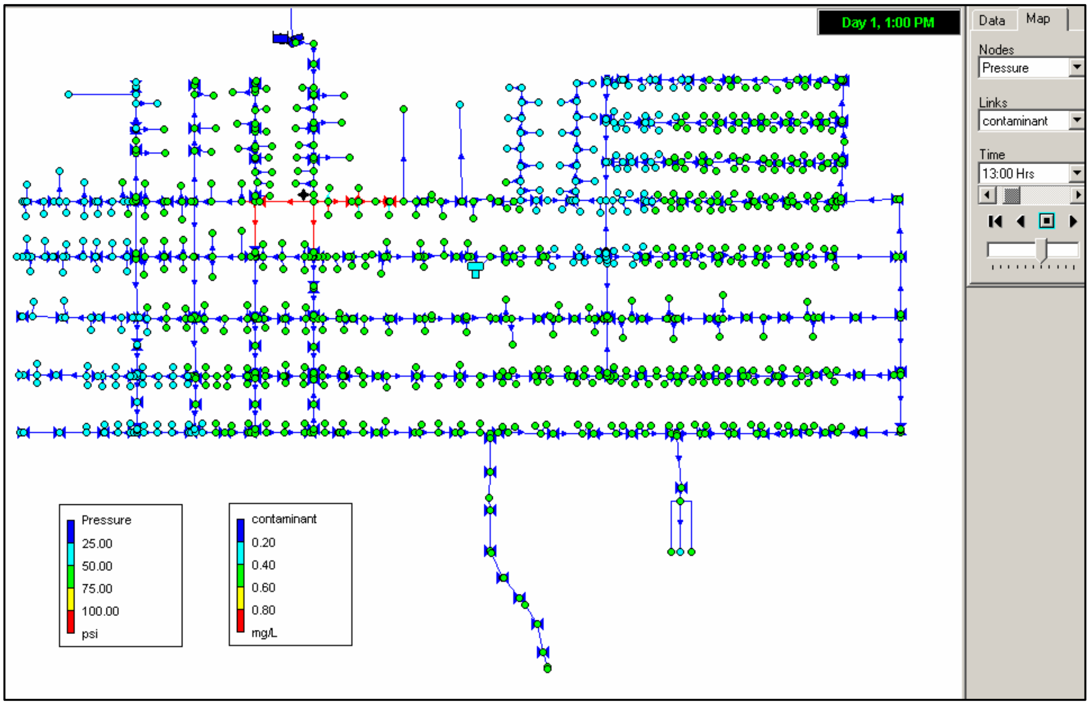
Fig. 8. Defining Contaminant and Event Duration

Snapshots of the simulation event are illustrated in chronological order in Figures 9 through 12. It is assumed that the toxicity of this hypothetical contaminant is fatal if ingested in water at a concentration greater that 0.8 mg/L, as indicated in red in the pipe legend of Figure 9. Traces of lethal contamination concentrations become noticeable half way into day one, as shown in Figures 10 and 11. Water contained in red pipes is considered lethal, water contained in yellow pipes is considered harmful, and water contained in blue pipes is considered safe for drinking.



Nodes: Pressure
Links: contaminant
Time: 0:00 Hrs

Fig. 9. Simulation at Day 1, 12:00 AM

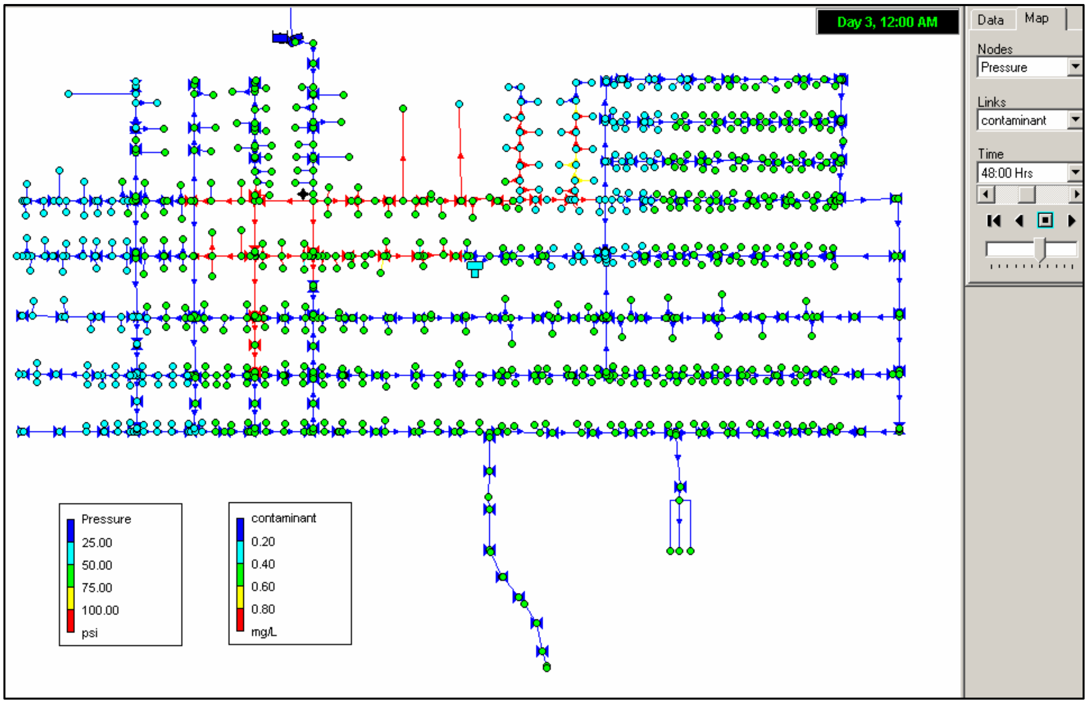


Nodes
Pressure

Links
contaminant

Time
13:00 Hrs

Fig. 10. Simulation at Day 1, 1:00 PM

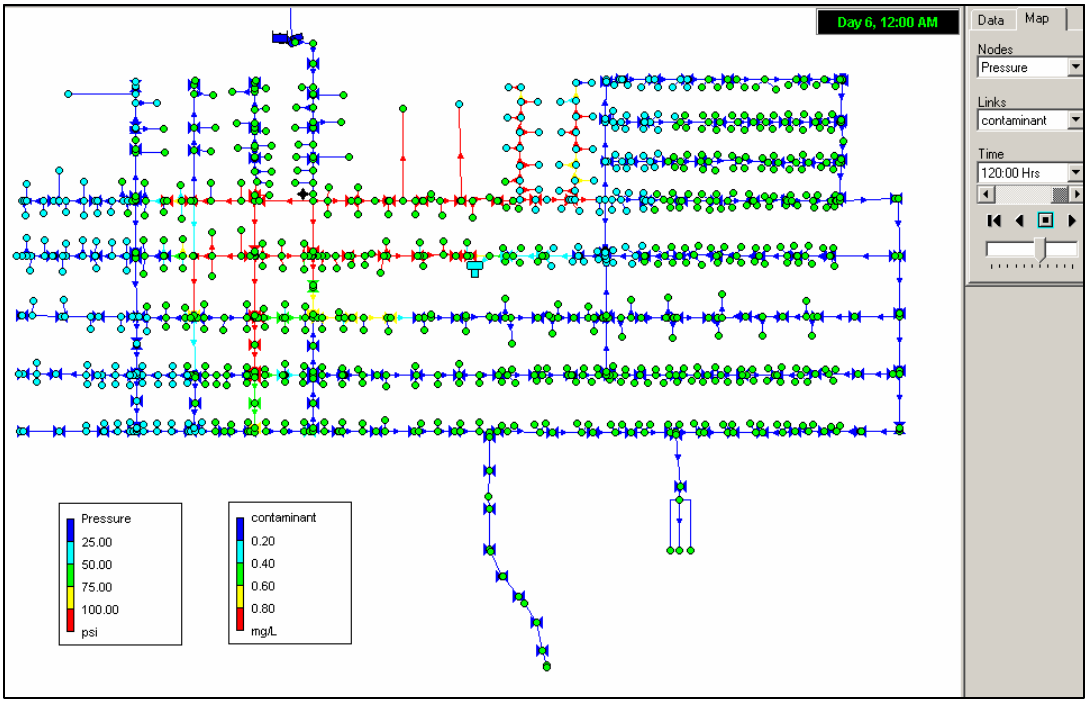


Nodes
Pressure

Links
contaminant

Time
48:00 Hrs

Fig. 11. Simulation at Day 3, 12:00 AM



Nodes
Pressure

Links
contaminant

Time
120:00 Hrs

Fig. 12. Simulation at Day 6, 12:00 AM

Skipping to the final time segment, it is shown in Figure 12 that the concentration ceases to spread beyond a general area. This is a result of first order reaction decay behavior. In time, the concentration of the contaminant decays linearly to zero.

The same contaminant and intrusion point are applied to Scenario 2, however the initial tank water level in Micropolis is reduced from 115 ft to 90 ft. The tank is shown in Figure 13. The concentration effect of this scenario is considered for the school as well. Results of Scenario 2 are presented in Chapter V.

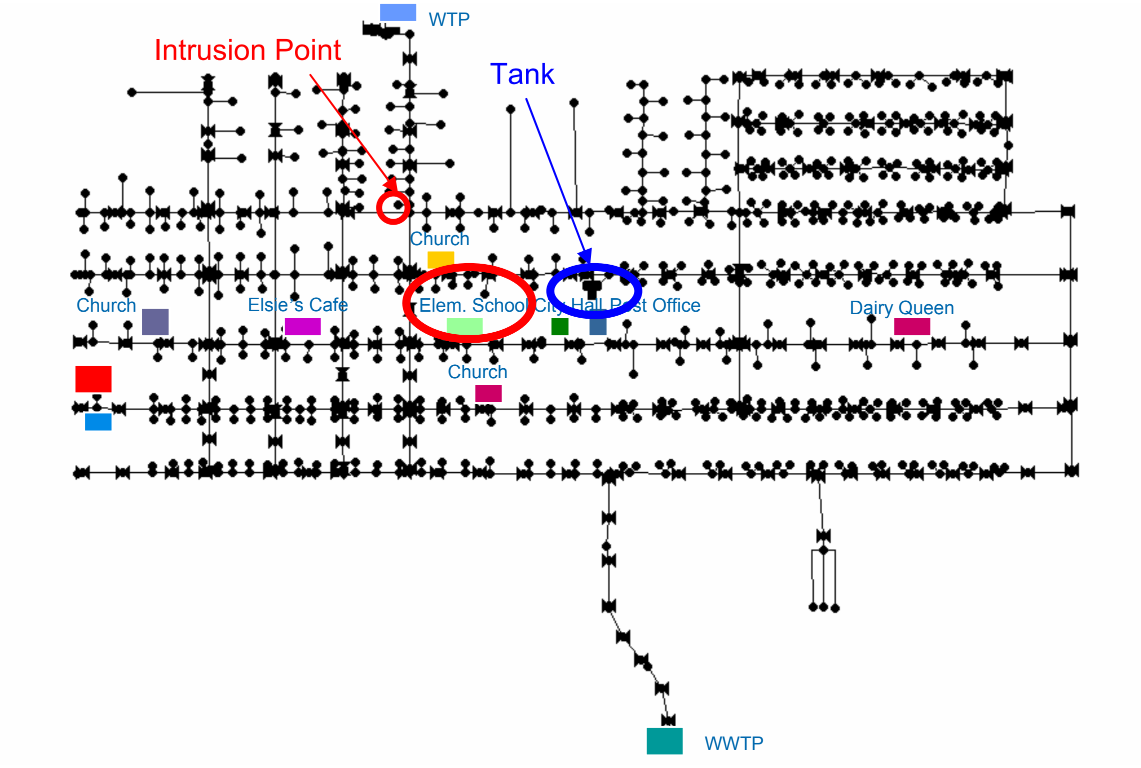


Fig. 13. Contamination Scenario 2

Finally, for Scenario 3, the contamination setup from Scenario 2 is maintained, however, the effect of a valve shutoff is considered. Valve 149 is the desired shutoff valve, as shown in Figure 14. The concentration effect of this adjustment is considered from the school's perspective. Results of Scenario 3 are presented in Chapter V.

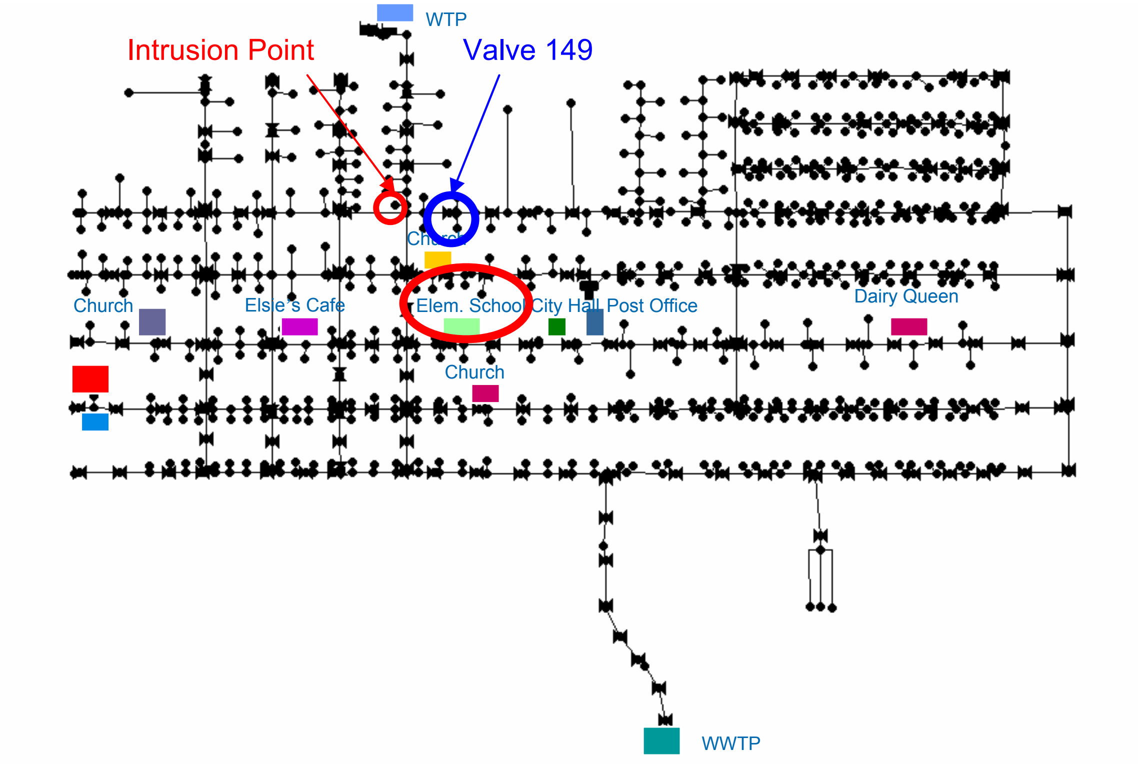


Fig. 14. Contamination Scenario 3

CHAPTER V

PHASE 3 – OBTAINING RESULTS

Phase 3 involves the analysis of results. Once the contamination was simulated for three scenarios, an examination of these results was performed to see resulting effects and impacts on those depending on the water for daily living. For purposes of this thesis, the effects of all three contamination scenarios were considered from the elementary school's demand dependency. Figure 15 presents a plot of the contaminant concentration behavior for the water being received at the school for Scenario1.

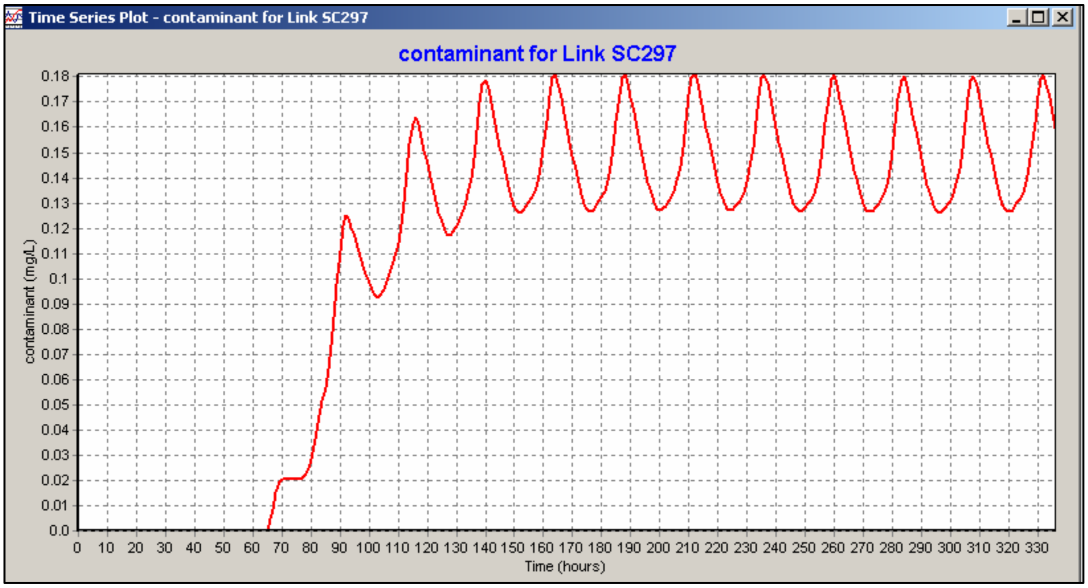


Fig. 15. Concentration Plot for Elementary School

It is shown that the contaminant concentration has no significant impact on the school until day three. At this time, there is an initial spike in concentration, but quickly tapers asymptotically in a sinusoidal fashion. The tapering behavior is an effect resulting from system equilibrium due to a continuous contamination source injecting the system at the same initial concentration over time. The oscillation behavior is justified by the school water demand patterns and contaminant decay as stated previously in Chapter 2. For a typical school, peak demands occur from 8:00 a.m.-5:00 p.m. This peak demand is reflected in the upward half of the oscillation wave in Figure 15. Higher demands result in higher concentration exposure. During low demand hours (such as at night) the contaminant remains in the system longer, therefore allowing decay to play a bigger role. This low demand is reflected in the downward half of the oscillation wave in Figure 15. Recall that this contaminant is fatal if ingested in water at a concentration greater than 0.80 mg/L. It is noted that the concentration never exceeds 0.18 mg/L throughout the duration of the event; therefore the school's drinking water is considered safe for Scenario 1.

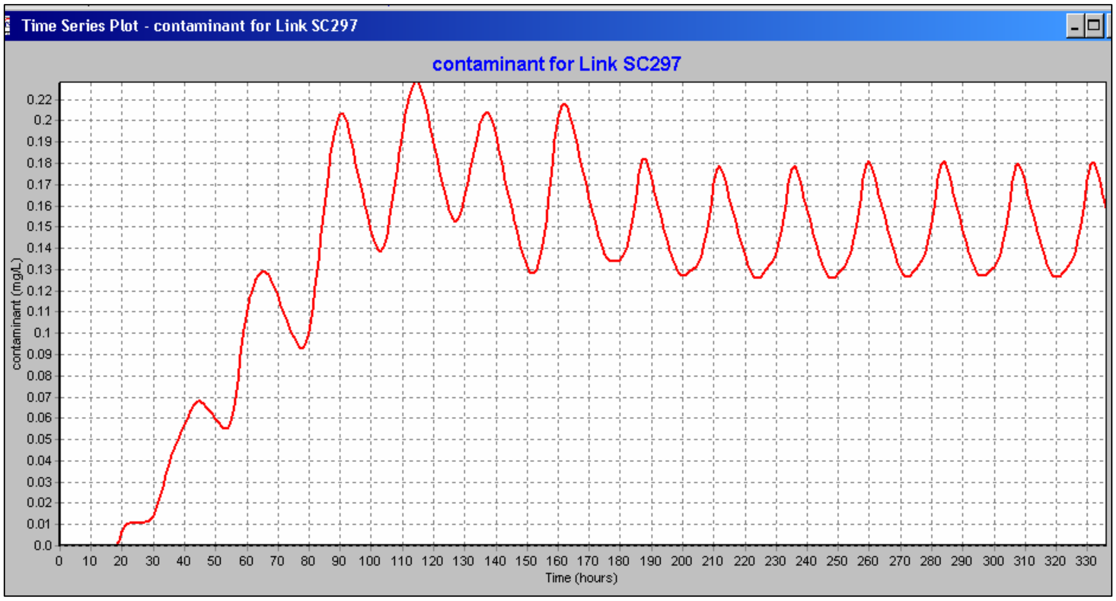


Fig. 16. Concentration Plot for Elementary School for Contamination Scenario 2

Results of contamination for Scenario 2 are shown in Figure 16. Recall that Scenario 2 involves a reduction in initial tank levels from 115 ft to 90 ft. Because less water is available in the tank during the initial stages of the simulation, the school receives more water from the water treatment plant (WTP). Looking closer at the location of the intrusion point, it is noted that the contaminant is injected into a major water main leading directly from the WTP. This reduction in tank water level results in the contaminant reaching the school at higher initial concentrations and approximately 45 hours sooner than in Scenario 1! The same justifications for the tapering and oscillation behaviors described for Scenario 1 also apply to Scenario 2. Figure 16 shows the concentration never exceeding 0.22 mg/L throughout the duration of the simulation; therefore the school's drinking water for Scenario 2 remains safe.

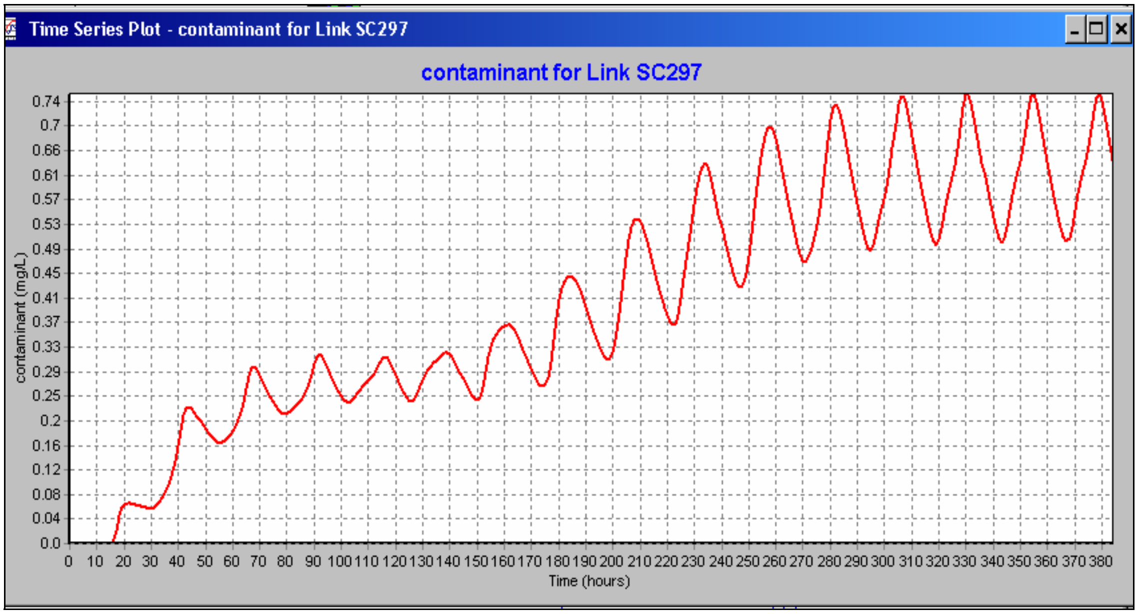


Fig. 17. Concentration Plot for Elementary School for Contamination Scenario 3

Results of contamination for Scenario 3 are shown in Figure 17. Recall that Scenario 3 involves the same system setup in Scenario 2, with the exception of closing Valve 149. Shutoff of this valve results in a partial isolation of contamination spread to northern Micropolis. Less spread in northern areas results in higher spread to southern areas. This results in a sooner contaminant arrival at the school. The same justifications for the tapering and oscillation behaviors described for Scenario 1 and 2 also apply to Scenario 3. Figure 17 illustrates the asymptotic concentration increase to a value of 0.74 mg/L. Note that this toxicity falls within the yellow pipe range. This concentration is enough to cause life threatening illnesses! It is concluded that Scenario 3 is considered dangerous and proper measures are to be taken to avoid this hazard.

Three scenarios have been presented, but there are many additional scenarios to simulate. It is hoped that an optimization will be developed for study of a worst case scenario. A worst case scenario will aid the planning process for maximizing an efficient emergency response procedure for Micropolis. This emergency response will involve isolating the contaminant for designated WDS areas, informing the public, ordering a “DO NOT CONSUME,” and/or evacuating the city residents.

CHAPTER VI

CONCLUSIONS

Though the probability of successfully contaminating an entire water distribution system is low, the possibility remains real. Micropolis provides researchers with a detailed and realistic virtual city for water distribution system research applications. Eventually, the development of a larger city will be used for continuation of this study. Professionals can use or contribute to this library of virtual cities for comparison of results or additional contamination scenarios. It is hoped that this research, and similar works, will provide scientists, engineers, and city decision makers with a better understanding on the issues pertaining to WDB contamination vulnerability and the necessary measures for making a city’s water distribution system less prone to accidental or intentional contamination events.

REFERENCES

Ductile Iron Pipe Research Association. (2005). <http://www.dipra.org> (Apr. 26, 2006).

Haestad Methods, Walski, T.M., Chase, D.V., Savic, D.A., Grayman, W.M., Beckwith S., Koelle E. (2003). *Advanced Water Distribution Modeling and Management*. 1st Ed. p. 147-150, 160. Haestad Press.

Rossman, Lewis A. (2000). *EPANet 2.0 User's Manual*. United States Environmental Protection Agency. National Risk Management Research Laboratory Office of Research and Development.

Wurbs, Ralph A and Wesley P. James. (2002). *Water Resources Engineering*. p. 135-136. Prentice Hall.

CONTACT INFORMATION

Name: Jacob Manuel Torres

Address: Zachry Department of Civil Engineering
3136 TAMU
College Station, TX 77843-3136

Email Address: jacob2701@yahoo.com

Education: B.S., Civil Engineering, Texas A&M University, 2006.