Developing Mesopolis – A "Virtual City" for Research in Water Distribution Systems and Interdependent Infrastructures

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Abstract: The ability of a water distribution system (WDS) to meet flow and pressure requirements under disaster conditions, e.g. fires or hurricanes, is vital. Currently available hydraulic analysis software can accurately simulate a WDS' ability to meet these requirements, but fails to account for interdependency with other infrastructures. The goal of this research is to develop a robust WDS model for Mesopolis, a "virtual city" with a population of 140,000, to integrate the WDS with power and communications infrastructure models through GIS software and other simulation packages, and to develop a methodology for modeling the interdependency of water, power, and communications infrastructures in disaster scenarios. Mesopolis' topography is defined in GIS software and its low-resolution WDS is modeled in EPANET, comprising two treatment plants and multiple pressure planes served by several storage tanks and booster stations. Extended-period hydraulic analyses of maximum-day and average-day demand scenarios have proven the WDS capable of handling fire flow demand. Further research is needed to successfully integrate the WDS model with power and communications models.

Keywords: Water distribution, power distribution, interdependent infrastructures

1. INTRODUCTION

Computer modeling of municipal infrastructures is essential for accurately predicting the behavior of water distribution networks over time and under various conditions. Desktop computers equipped with software packages such as EPANET make these calculations accurate and efficient. This can help to ensure economical operation of the network's pumps and tanks, and also to expose its weaknesses during peak usage periods – for example, low pressures at service connections or extreme energy losses in pipelines.

Mesopolis, a "virtual city" with a population of 140,000, is being built using the software packages ArcGIS and EPANET to act as a realistic test-bed for water, power, and communications infrastructures. Since the Mesopolis model is a generic city with no real-world counterpart, all future analysis and discussion of the model can be freely shared without security concerns.

In real-world operation, a water distribution network is dependent on other infrastructures – a water distribution pump station relies on a power source, and a water-quality-monitoring SCADA system often relies on a wireless communications network. If one of these supporting infrastructures fails, there will be negative effects on the water distribution system; however, current water modeling software packages are not equipped to consider these dependencies. After further research and collaboration with electrical engineering and computer science researchers, a straightforward methodology for modeling interdependent infrastructures will be presented using Mesopolis as a test case.

2. A BRIEF HISTORY OF MESOPOLIS

Mesopolis was first conceived as a quintessential U.S. city, combining aspects of East Coast, Gulf Coast, and West Coast geography and layout – it was first settled in the 18th century, has a hot and humid Texas climate, leading to increased water usage, and also features two mountainous peninsulas, which form a 7-mile-wide bay. By 1720, the main port in the southwest area of the bay supported a population of 5,000. There was no significant population growth until 1800, when the river that drained into the bay was channelized; the new commerce this brought to the region allowed the population to swell to 20,000 by 1830. By the late 1800s, industrial development along the river in the paper, textile, and lumber industries had flourished to 40,000. A land grant university was established east of the eastern ridge in 1870; and by 1910, heavy industry in metals, iron, and chemicals had developed just east of the river, while the lumber industry adjacent to the river collapsed and the textile mill closed.

It was in 1910 that the city government decided to build a municipal water distribution system (WDS) in response to a typhoid outbreak. Since many industry byproducts were being dumped into the river, the WDS intake pumps were installed on the river 20 miles inland, pumping raw river water to a treatment plant at the western port, near the site of the original settlement. This fledgling WDS would initially serve a population of 60,000. A naval base was constructed west of the western ridge in the 1940s, while suburban developments continued to expand. In 1970, the heavy industry east of the river collapsed, while the university and the naval base continued to draw people to Mesopolis. In 1980, suburban growth in the foothills of the eastern mountains prompted construction of a second water treatment plant, which draws its water from the same raw water pipeline that serves the western treatment plant. Finally, Mesopolis' suburban and residential areas have continued to expand over the western and eastern ridges, bringing the total population to about 140,000.

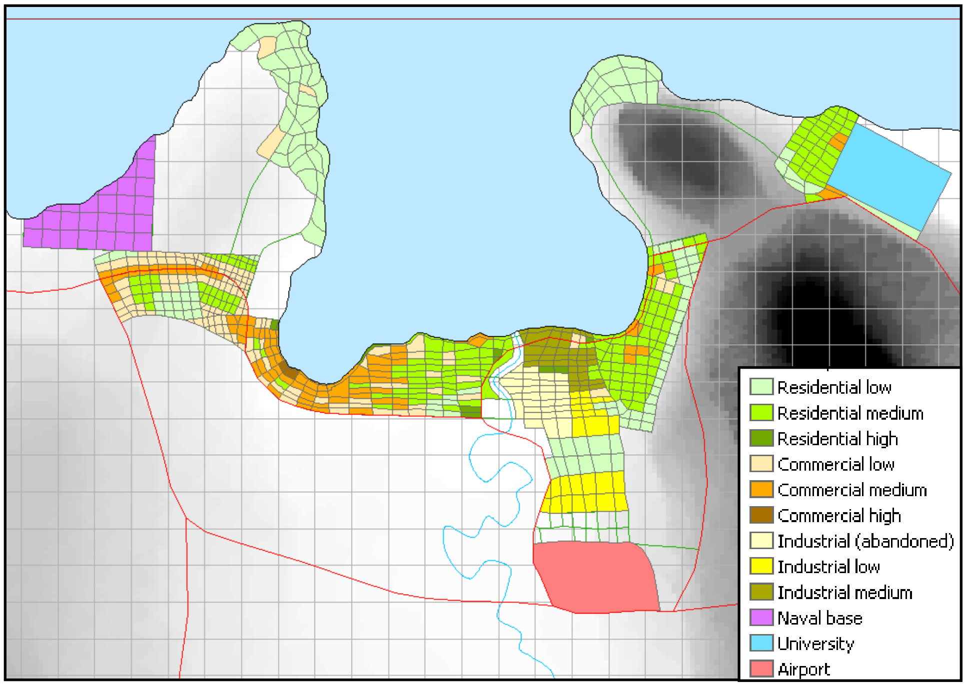

Figure 1: Mesopolis overview
(Grid scale: 1 mile x 1 mile.)

3. MAPPING MESOPOLIS

The city's rich "history" was used as a guide for mapping the highways, major and minor arterial roads, land-use distribution, and population density, which determine the water demands in the EPANET model of the low-resolution WDS. First, a network of roads was drafted into ArcGIS; the resulting grid was used to split the city into 737 individual blocks. (See Figure 1, above.) Each block of color in the map, from 10-100 acres, represents a land-use type and density: residential, commercial, or industrial zones, in low, medium and high densities.

Each land-use type was assigned a typical water demand in gallons per day per acre for a Texas climate [Water Distribution Systems Handbook, Mays, 2000, 3.5]. Refer to Table 1, below. A base water demand in gallons per minute was calculated for each block. The grid of 737 blocks was then labeled with its water demand and exported as a metafile image map to EPANET 2.00.09a, where the water distribution network would take shape.

Land-Use-Type	***Low/med/high density demand***	
Commercial	400/700/1000	gpd/acre
Industrial	200/400/600	gpd/acre
Residential	600/900/2600	gpd/acre
Airport	45,000	gpd
Naval base	3,300,000	gpd
University	4,300,000	gpd

Table 1: Typical water demands.

4. MODELING MESOPOLIS' WATER DISTRIBUTION SYSTEM

4.1. Introduction

The low-resolution WDS is modeled in EPANET as a grid of connected intermediate nodes at roadway intersections, which connect to a series of terminal nodes, each denoting an aggregated demand for the land-use block it occupies. (Refer to Figure 2, below.) The distribution network is composed of various diameters and pipe materials in an attempt to simulate the properties of an aged WDS that has undergone a hodge-podge of upgrades and replacements. For example, the port area that was first settled in the 18th century is still served with 2-inch and 4-inch cast iron mains, some of which have been upgraded to 12-inch ductile iron, while newer suburban areas are served with 12-inch and 18-inch polyvinylchloride mains.

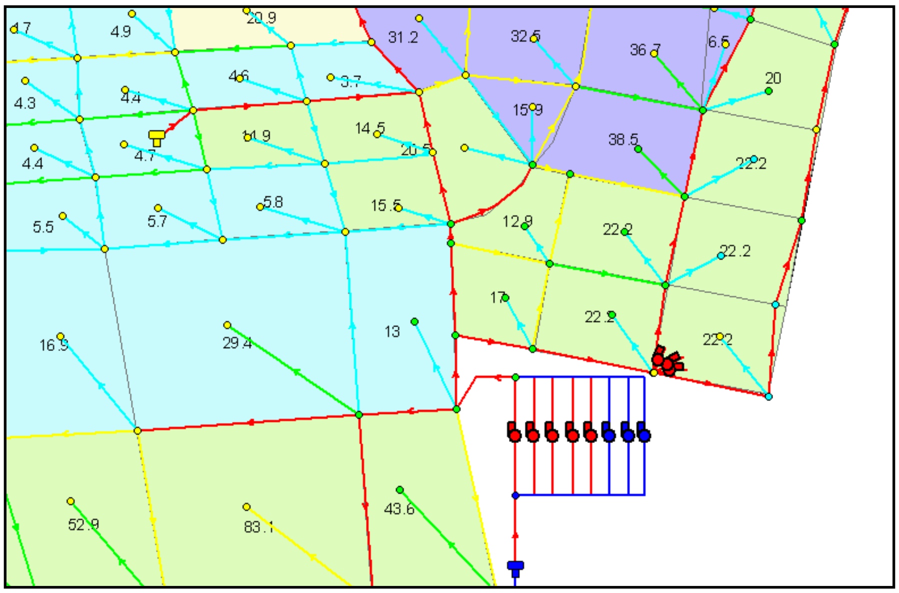

Figure 2: Close-up of the eastern treatment plant area.

4.2. Pumps

All pumps used in the Mesopolis model were chosen using pump curves obtained from ITT Corporation's ePrism Pump Selection Service (http://eprism.gouldspumps.com/prism/). These pump curves describe the hydraulic head (energy) supplied by the pump as a function of the flow rate through that pump. The two water treatment plants that pressurize the distribution network are each modeled using eight pumps which drawing from a large reservoir tank of raw river water. Both reservoir tanks are fed by seven Gould's 3420 model pumps, size 20x24x30 DV-M with 26.875-inch impellers, capable of pumping 105,000 gpm (or 151 mgd).

The older, western treatment plant uses Gould's 3410 model pumps, size 10x12-14 L with 12.75-inch impellers, and is capable of pumping 32,000 gpm (or 46 mgd). Its raw water tank draws its water from an old 36-inch cast-iron main, as well as a newer 48-inch ductile-iron main. The newer, eastern treatment plant uses Gould's 3410 model pumps, size 10x12-12L with 12.375-inch impellers, and is capable of pumping 36,000 gpm (or 52 mgd). Its raw water tank draws its water exclusively from a 60-inch polyvinylchloride main. Since the eastern plant's elevation is 58 feet higher than the western plant, another raw water pump station containing five Gould's 3420 model pumps is required to further pressurize the 60-inch main, giving the water enough energy to fill the eastern plant's raw water tank.

4.3. Pressure Planes

The ultimate purpose of the WDS is to provide the flow demanded at each terminal node within acceptable limits of pressure. To satisfy environmental regulations, pressures at all points in the system must remain above 35 psi at all times. In the process of designing this model, I attempted to keep pressures at terminal nodes below an upper limit of 80 psi. Water provided to the university must cross over the eastern ridge, a span of about 3 miles with an elevation difference of 390 feet. To use a single, large pump station to provide enough energy to cross the ridge would require a pressure at the base of the mountain of: $35\frac{\text{lb}}{\text{in}^2} + 390\text{ ft} \times 62.4\,\frac{\text{lb}}{\text{ft}^3} \div 144\frac{\text{in}^2}{\text{ft}^2} = \mathbf{204\ psi}$. Thus, I chose to use smaller pump stations in series. See Figure 3, below, for an illustration of the pipeline crossing the eastern ridge.

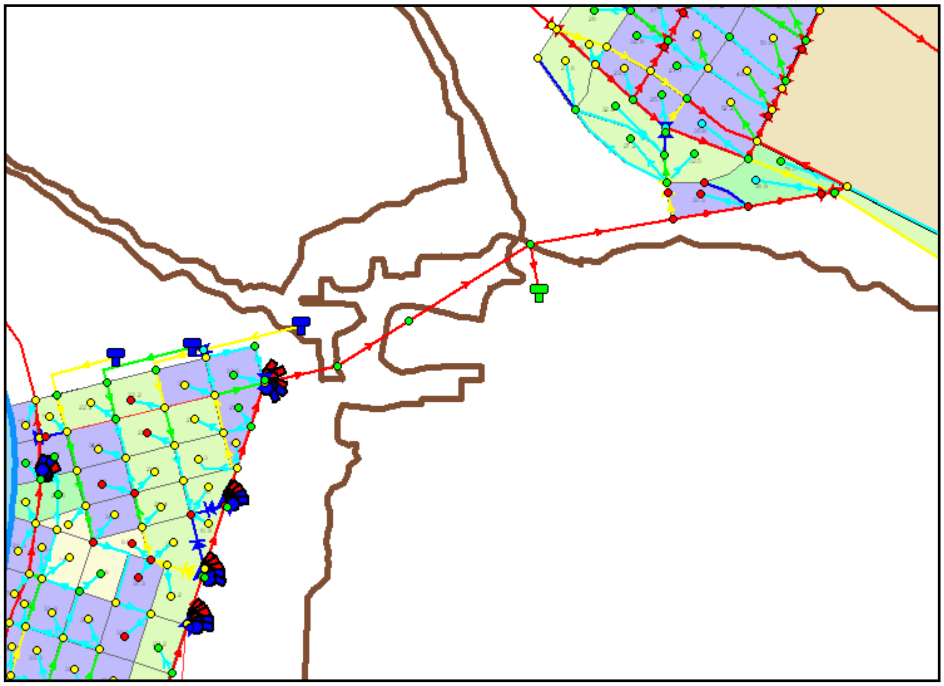

Figure 3: Pipeline crossing the eastern ridge.

Some of the water that is pressurized by the first pump station in the series (say, pump station A) is able to serve the residential development in the lowest foothills, while the next pump station (B) is able to serve the developments that are higher up the ridge, and so on. This creates what are called “pressure planes” – isolated portions of the WDS, located at different elevations, which are specifically pressurized by a specific pump station or tank. If the highest terminal node in pressure plane A is not to drop below 35 psi, and the lowest terminal node in pressure plane B is not to be pressurized above 80 psi, then the two adjacent pressure planes should have an average elevation difference of, at most, 104 ft. (Convert the pressure limits into hydraulic head in feet: $80\,\frac{\text{lb}}{\text{in}^2} \times 144\,\frac{\text{in}^2}{\text{ft}^2} \div\ 62.4\ \frac{\text{lb}}{\text{ft}^3} = \mathbf{185\ ft}$, and $35\,\frac{\text{lb}}{\text{in}^2} \times 144\,\frac{\text{in}^2}{\text{ft}^2}\ /\ 62.4\ \frac{\text{lb}}{\text{ft}^3} = \mathbf{81\ ft}$. The difference is $\mathbf{104}$ **ft**.) At the eastern ridge of Mesopolis, five pump stations, equipped with various sizes of Gould’s 3410 pumps, separate the WDS into six separate pressure planes, yielding more conservative pressure limits for each pressure plane. Each pressure plane also has at least one tank, which fills during the evening and drains during the day, easing the load on the pump stations and using energy more efficiently.

Figure 4, below, is a closer view of the west slope of the eastern ridge, showing each pressure plane more clearly. Note that each plane is isolated from the others, and that each plane is pressurized by an individual booster station and connected to its own hillside tank.

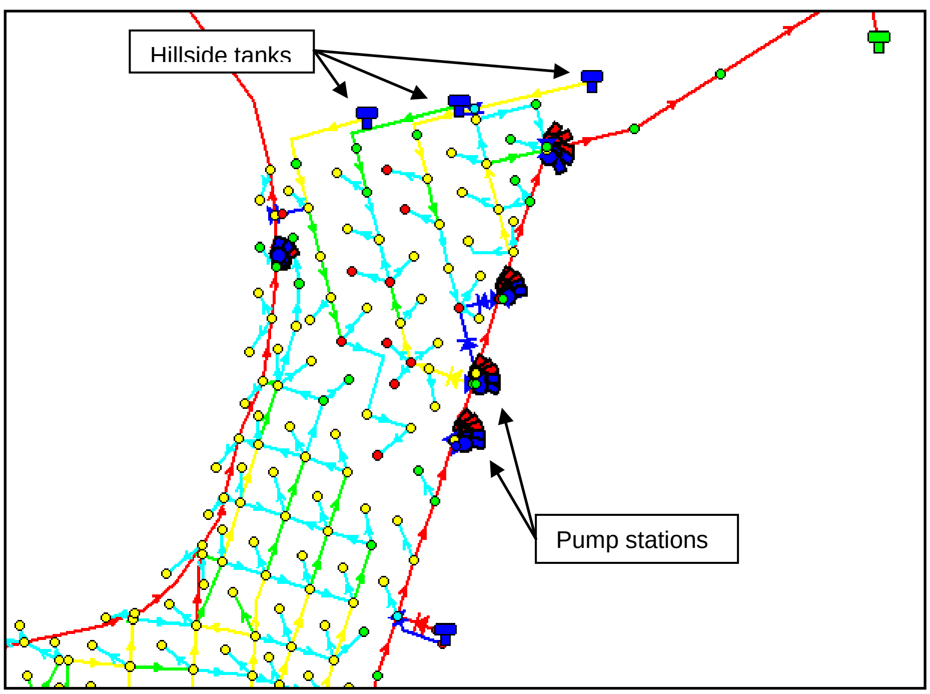

Figure 4: Multiple pressure planes near the eastern ridge.

At the top of the mountain, in the center of Figure 3, is a water tower placed at the pipeline's highest point. This tower aids in maintaining the minimum required pressure of 35 psi in the pipeline, and also serves as a reservoir to the university on the eastern side of the ridge. To prevent excessive pressure at the eastern base of the ridge, a series of pressure-reducing valves (PRVs) is used to induce energy losses in the pipeline. EPANET's valve editor contains a parameter for the maximum pressure allowed on the downhill side of a PRV. In Mesopolis, this PRV parameter is set for high pressures – between 60 and 75 psi.

4.4. Tanks

To ensure that Mesopolis' WDS is able to meet fire flow requirements, a group of water towers and hillside tanks is connected to the network. Under normal daily operation, the levels of these tanks must oscillate between a full value at the beginning of the day and a minimum value during peak usage times. The minimum tank level value is determined using the fire flow volume required by city code. Minimum Mesopolis fire flow volumes depend on land-use type [Mays, 3.5], and are listed in Table 2, below. In addition, flows less than 3,000 gpm must be sustained for 2 hours; flows between 3,000-4,000 gpm must be sustained for 3 hours; and any flow higher than 4,000 gpm must be sustained for 4 hours [Mays, 10.14].

Land-use type	***Fire flow requirements (gal/min)***
Single-family residential	500-2,000
Multi-family residential	1,500-3,000
Commercial	2,500-5,000
Industrial	3,500-10,000
Central business district	2,500-15,000

Table 2: Typical fire flow requirements.

So, for example, the highest hillside tank on the western slope of the eastern ridge (see Figure 4), which provides fire flow for a single-family residential development, should always contain a minimum reserve volume of $2{,}000\,\frac{\text{gal}}{\text{min}} \times 2\ \text{hr} \times 60\ \frac{\text{min}}{\text{hr}} \div 7.48\,\frac{\text{gal}}{\text{ft}^3} = \mathbf{32{,}000\ ft^3}$. The bottom elevation of each tank is set such that the fire flow requirements are met during the peak hour water demand under maximum day conditions (this is often during the late afternoon in the hottest summer months).

4.5. Diurnal Demand Patterns

Water demands in a WDS fluctuate during the day, dropping to a minimum value at night and rising to a maximum at mid-morning and again in the late afternoon. This is called a diurnal demand pattern. EPANET is capable of performing extended period analysis by adjusting the demand at each terminal node every hour and recalculating the mass and energy conservation equations. A natural pattern begins to emerge, with pressures dropping during the day as the tanks empty their volumes into the network, and pressures rising at night as the tanks are filled by pumps at the treatment plants and booster stations. The demand for each terminal node is considered its base demand, which is multiplied by a series of multipliers as EPANET's extended period simulation progresses. This series of multipliers constitutes the diurnal demand pattern, and depends on the land-use type. See Figure 5, below, for examples of diurnal demand patterns.

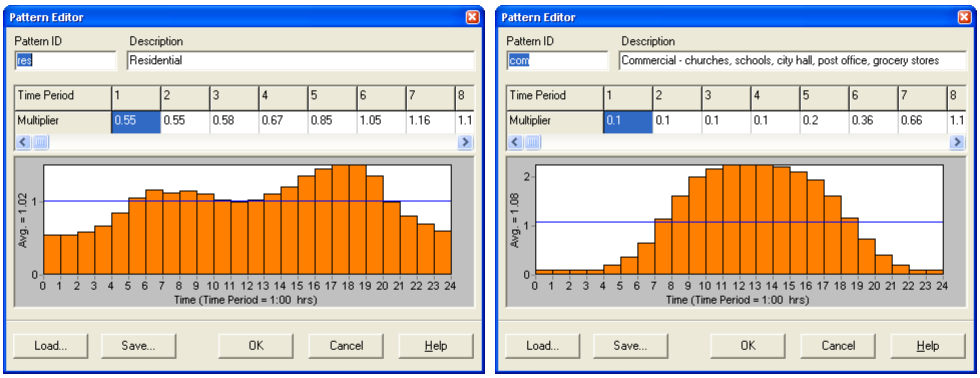

Figure 5: Diurnal demand patterns.

4.6. Maximum Day Demand vs. Average Day Demand

Though diurnal demand patterns are able to describe periodic changes throughout the day, there is no way to describe the gradual change in demand between seasons. In order to ensure Mesopolis' ability to handle the maximum day demand in the summer, an overall peaking coefficient is applied to the system. Typical peaking coefficients relating maximum day demand (MDD) to average day demand (ADD) range from 1.8-2.8. Mesopolis uses a peaking coefficient of 2.5. Thus, to apply MDD conditions, EPANET will automatically multiply the ADD demands – the base demands assigned to each terminal node – by a factor of 2.5. The diurnal demand patterns are then multiplied by the MDD values for each time step.

The tanks were designed with the EPANET model set to an MDD scenario, with the assumption that the change in tank levels should be greatest when demand is highest, and that all pump stations would be operating continually. After all tanks were set to drain to the minimum fire flow, the EPANET model was returned to ADD. At this point, running the ADD model with all pump stations operating would not allow the tanks to drain. This poses a water quality issue, as the concentration of residual disinfectant (usually chlorine) decays with time. Water that remains in a tank for more than a few days will eventually allow growth of bacteria or microbes. So it is important that tanks are allowed to have an appreciable fluctuation in volume throughout the day. In an ADD scenario, this is accomplished by turning off key pump stations during the day, only operating them at night to refill the tank. This allows the tanks to provide energy to the WDS during the day, and saves operating costs.

4.7. Controls

EPANET contains a library of controls that can be used to dynamically adjust properties of the network during extended period analysis; these controls take the form of “if-then-else” statements. In Mesopolis, these controls are used to keep pumps operating at maximum efficiency throughout the day, to turn pumps on if a tank’s volume is too low, and to allowing tanks to drain. MDD and ADD scenarios each have unique controls.

For example, a pump at the western treatment plant operates at maximum efficiency when its flowrate is between 2,000 and 4,000 gallons per minute. The controls for this pump ensure that, if more than 4,000 gpm begins to flow through the first pump, more are switched on until all pumps are operating within their efficiency limits.

Another set of complex rules manages the tanks and pump stations on the eastern ridge. Refer back to Figure 4 to see the series of pump stations (named eboost-c, -d, -e, and -f, going uphill) serving the mountain tank and three hillside tanks (named hillside-tank1, -tank2, and -tank3, going downhill). These rules ensure that, under the ADD scenario, each pump station will operate only if it is necessary to refill one of the tanks above its minimum value.

```
RULE 1
IF TANK mtn-tank LEVEL BELOW 116
OR TANK mtn-tank FILLTIME ABOVE 30
AND SYSTEM CLOCKTIME >= 4 PM
OR  SYSTEM CLOCKTIME <= 7 AM
THEN PUMP eboost-f1 STATUS IS OPEN
AND  PUMP eboost-e1 STATUS IS OPEN
AND  PUMP eboost-d1 STATUS IS OPEN
AND  PUMP eboost-c1 STATUS IS OPEN
AND  PUMP eboost-b1 STATUS IS OPEN
AND  PUMP hspe1 STATUS IS OPEN
AND  LINK MAeboost-f-byp STATUS IS CLOSED
ELSE PUMP eboost-f1 STATUS IS CLOSED
AND  PUMP eboost-f2 STATUS IS CLOSED
AND  PUMP eboost-f3 STATUS IS CLOSED
AND  PUMP eboost-f4 STATUS IS CLOSED
AND  PUMP eboost-f5 STATUS IS CLOSED
AND  PUMP eboost-e1 STATUS IS CLOSED
AND  PUMP eboost-e2 STATUS IS CLOSED
AND  PUMP eboost-e3 STATUS IS CLOSED
AND  PUMP eboost-e4 STATUS IS CLOSED
AND  PUMP eboost-e5 STATUS IS CLOSED
AND  PUMP eboost-d1 STATUS IS CLOSED
AND  PUMP eboost-d2 STATUS IS CLOSED
AND  PUMP eboost-d3 STATUS IS CLOSED
AND  PUMP eboost-d4 STATUS IS CLOSED
AND  PUMP eboost-d5 STATUS IS CLOSED
AND  PUMP eboost-c1 STATUS IS CLOSED
AND  PUMP eboost-c2 STATUS IS CLOSED
AND  PUMP eboost-c3 STATUS IS CLOSED
AND  PUMP eboost-c4 STATUS IS CLOSED
AND  PUMP eboost-c5 STATUS IS CLOSED
AND  PUMP eboost-b1 STATUS IS CLOSED
AND  PUMP eboost-b2 STATUS IS CLOSED
AND  PUMP eboost-b3 STATUS IS CLOSED
AND  LINK MAeboost-f-byp STATUS IS OPEN
PRIORITY 4
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RULE 2
IF TANK hillside-tank1 LEVEL BELOW 13
OR TANK hillside-tank1 FILLTIME ABOVE 30
THEN PUMP eboost-d1 STATUS IS OPEN
AND  PUMP eboost-c1 STATUS IS OPEN
AND  PUMP eboost-b1 STATUS IS OPEN
PRIORITY 5
RULE 3
IF TANK hillside-tank2 LEVEL BELOW 13
OR TANK hillside-tank2 FILLTIME ABOVE 30
THEN PUMP eboost-c1 STATUS IS OPEN
AND  PUMP eboost-b1 STATUS IS OPEN
PRIORITY 5
RULE 4
IF TANK hillside-tank3 LEVEL BELOW 12
OR TANK hillside-tank3 FILLTIME ABOVE 30
THEN LINK MA0883 STATUS IS OPEN
ELSE LINK MA0883 STATUS IS CLOSED
PRIORITY 5
RULE 5
IF TANK hillside-tank4 LEVEL BELOW 15
OR TANK hillside-tank4 FILLTIME ABOVE 30
THEN PUMP eboost-b1 STATUS IS OPEN
AND  LINK MAtank4in STATUS IS OPEN
ELSE LINK MAtank4in STATUS IS CLOSED
PRIORITY 5
RULE 6
IF TANK mtn-tank LEVEL BELOW 116
OR TANK mtn-tank FILLTIME ABOVE 30
AND SYSTEM CLOCKTIME >= 4 PM
OR  SYSTEM CLOCKTIME <= 7 AM
OR TANK hillside-tank1 LEVEL BELOW 13
OR TANK hillside-tank1 FILLTIME ABOVE 30
OR TANK hillside-tank2 LEVEL BELOW 13
OR TANK hillside-tank2 FILLTIME ABOVE 30
THEN LINK MAtank4out STATUS IS CLOSED
ELSE LINK MAtank4out STATUS IS OPEN
PRIORITY 4
```

Table 6: Example controls.

Rule 1 will fill the tank at the top of the mountain at night, but only if the water level is below 116 feet above the ground. (This is the minimum value required to maintain sufficient fire flow volume.) The "or filltime above 30" condition simply ensures that, if the tank is being filled, the pump stations are not shut off before the tank is almost completely filled. Notice that the "then" statement only turns on one pump from each pump station. Another set of rules turns on the other pumps if they are needed, for efficiency. Rule 1 has a priority level of 4, meaning that only a priority-level-5 rule can override it.

Rules 2 and 3 allow the hillside tanks to be filled, even if the mountain tank is not being filled. They activate the minimum required number of pump stations to fill the tank. Rules 4 and 5 are slightly more complex, as they deal with opening and closing certain pipelines (links) in addition to controlling the status of pumps. Notice that Rules 2-5 take priority over Rule 1 – they must, since Rule 1 would shut off each pump station by default after the mountain tank is filled.

Finally, Rule 6 fixes a problem in which hillside-tank4 would empty rapidly, sometimes within one hour, while the mountain tank or one of the first two hillside tanks was being filled. Its "if" statements mimic those of Rules 1-3, and if they are satisfied (that is, if either mtn-tank, hillside-tank1, or hillside-tank2 are being filled), then hillside-tank4 is not allowed to drain.

These are only a few examples of the many controls necessary to operate Mesopolis' ADD model. At the time of this writing, ADD controls successfully manage the levels 9 of Mesopolis' 13 tanks, but are not yet completed.

5. RESULTS AND FUTURE PLANS

The development of Mesopolis is just beginning. The low-resolution EPANET network model will be published online at http://ceprofs.tamu.edu/kbrumbelow/, where it will be fine-tuned as research progresses. Nested high-resolution versions of the network are also in plans for development. These networks will feature small sections of Mesopolis modeled at a much higher level of detail – down to the individual valves and service connections.

After the low-resolution model is completed, my first task will be to complete a full analysis of the average water age in the system, and to model the decay of residual chlorine disinfectant in the network. With a system as large as Mesopolis', it seems obvious that there may be water age problems during the average day demand scenario. Some of the pump stations may need to be supplemented with chlorine boosters, or controls may need to be tweaked to allow the tank levels to oscillate more quickly.

The next goal is to integrate Mesopolis' WDS with power and communications infrastructure models, which are yet to be modeled by fellow researchers in electrical engineering. Ideally, each critical point in the power supply network will be associated with a certain pump station, so that when the power infrastructure experiences downtime at a specific time step, the pump station will be switched off in EPANET as well. To accomplish this, a wrapper program will need to be written in Visual Basic or C++. This wrapper will use the GIS map and/or a set of "if" statements to relate the infrastructure models to one another. EPANET's DLL scripting interface will allow EPANET to run the hydraulic simulation one time step at a time, waiting for input before proceeding. The goal is to have a power distribution network simulator, such as PSCAD, run its simulation alongside EPANET, outputting its results at each time step to a text file, which will in turn be read by the wrapper and used to determine which pump stations EPANET should take out of commission. After a certain delay, power may be returned to the disabled pump stations which are fitted with backup generators.

After the wrapper program successfully integrates the water and power distribution systems, several natural disasters may be simulated between the two programs, for example, a simulation of an urban fire spread disaster, or recovery from damage caused by a hurricane. Steps can then be taken to ensure that Mesopolis' infrastructure is repaired or supplemented at its weakest points, and we can discuss methodologies for limiting the damage caused by these disasters.

Dozens of actual cities and urban areas already have their utilities fully mapped and described in GIS format. As the Mesopolis model matures, we hope to discover new and effective methodologies for managing interdependent infrastructures that can be tailored for each unique application. We also hope that the openness of the Mesopolis model will encourage this collaborative development, and that, ultimately, urban citizens across the globe will reap the benefits.