AN ASSESSMENT OF THE WATER DISTRIBUTION SYSTEM IN THE CITY OF MEDFORD, MASSACHUSETTS

Yogesh Jitoo[1], Irvine Wei[2], Thomas R. Morgan[3], and Donald Ouellette[4]

ABSTRACT

The objective of this paper is to present the analysis of the water distribution system for the City of Medford, Massachusetts. H_2OMAP Water Suite, modeling software, was used to assess the system, and using the calibrated hydraulic model of the water distribution system, the current available fire flows were compared to the required fire flows as determined by the Insurance Services Office (ISO) in 2002. Further, the influence of improvements made by the City to the distribution system from 2002 through 2004 to meet the required fire flows was evaluated. The model was also used to determine the adequacy of the existing distribution system for current and future water needs.

For the locations failing to satisfy the fire flow criteria, several alternative upgrade scenarios were analyzed with the model to find the most appropriate improvements for the system. The recommendations are divided into two phases: First and Second priority. The total cost of these recommendations approximates 25 million dollars.

KEYWORDS:

Water Distribution System, Fire Flows, Hydraulic Model, Computer Software, Calibration

INTRODUCTION

Water distribution modeling is the latest technology used for evaluating existing water distribution systems and planning for future development. This tool helps to identify deficient areas in a distribution system and determine appropriate improvements necessary to make the system effective. With the use of the hydraulic modeling technology, the water distribution system for City of Medford, Massachusetts was evaluated for its capability to meet current and future water demand needs.

[1] Engineer, Weston & Sampson Engineers, Five Centennial Drive, Peabody, Massachusetts 01960, U.S.A., Phone 978/532-1900, FAX 978/977-0100, jitooy@wseinc.com

[2] Associate Professor, Dept. of Civil & Envir. Engrg. , Northeastern University, 360 Huntington Avenue, Boston, Massachusetts 02115, U.S.A., Phone 617/373-3368, FAX 617/373-4419, iwei@coe.neu.edu

[3] Vice President, Camp Dresser & McKee, One Cambridge Place, 50 Hampshire Street, Cambridge, Massachusetts 02139, U.S.A., Phone 617/452-6588, FAX 617/452-8588, morgantr@cdm.com

[4] City Engineer, Dept. of Public Works, City of Medford, 85 George P. Hassett Drive, Medford, Massachusetts, 02155, U.S.A., Phone: 781/393-2476, FAX 781/393-2342, douellette@medford.org

BACKGROUND

The majority of the City's distribution system dates back to 1900s, and consists mostly of unlined cast iron pipes. Although unlined cast iron pipes resist corrosion sufficiently to prevent failure, their carrying capacity maybe severely impacted. As corrosion reactions occur on the inner surface of the pipe, the reaction by-products expand to form an uneven pattern of lumps (Figure 1) in a process called tuberculation. Due to tuberculation in the city's aged water mains, the relative pipe carrying capacity has been reduced substantially since the mains were initially installed. As a result, the city's distribution system had problems with low fire flow, rusty water at the consumer's end and water main breaks.

Figure 1: Tuberculated Pipes

ISO surveyed Medford's distribution system in 2002 and provided a list of available fire flows and required fire flows at several locations throughout the city. The list provided by ISO showed that Medford's water distribution system had deficient fire flow areas.

The distribution system was evaluated in 1986 by Anderson-Nichols & Co. Inc., and also in 2002 by Camp Dresser & McKee Inc (CDM) to identify and quantify the cause and possible solutions for low fire flow problems. Using their evaluations, in an attempt to improve the distribution system, the city has recently completed major upgrades to its water distribution system by replacing and/or rehabilitating certain water mains and conducting a uni-directional water main flushing program. An up-to-date hydraulic model of the system that incorporated these improvements was needed to accurately assess the existing water distribution system.

DESCRIPTION OF THE WATER DISTRIBUTION SYSTEM

Medford's water distribution system has been servicing the city since the 1870s and is operated and maintained by its Public Works Department. It serves a current population of approximately 55,000 and consists of about 135 miles of water mains with pipe diameters ranging from four to sixteen inches. The majority of the water mains dates back to 1900s, and consists of unlined cast iron pipe.

The city's water distribution system is composed of two major pressure zones; the low-pressure zone and high pressure zone, which is a result of non-uniform topographical areas throughout Medford. In addition, one relatively small water booster station on Doonan Street Supplies water to a "super" high-pressure zone in the north high zone.

The city currently receives its entire water supply from the Massachusetts Water Resources Authority (MWRA) transmission mains. A total of 10 metered connections to the MWRA system mains are located throughout the city as the MWRA transmission mains traverse the city. The low-pressure system is serviced from the MWRA low service system by four metered connections. The northern high-pressure system is serviced by four metered connections, and the southern high is serviced by two metered connections from the MWRA high service system.

The city operates five pressure reducing valves (PRVs). Each PRV can be used to feed water from high-pressure zones to low-pressure zones when the pressure drops below the preset PRV pressure settings.

WATER SYSTEM DEMAND

Water system demands required for the system to meet its current and future (2025) needs are as shown in Table 1. The population projections and water consumption data are as calculated by CDM in its September 2002 report "Water Distribution System Master Plan" for Medford. The city's population has been decreasing steadily since 1960. For this study, the current population is considered to be same as the future population (2025).

Table 1: Water Consumption Data

Population	55,765 People
Per Capita Demand	100 gpcd[5]
Average Day Demand	5.58 MGD[6]
Maximum Day/ Average Day Ratio	1.8
Maximum Day Demand	10.04 MGD
Peak Hour/Average Day Ratio	2.8
Peak Hour Demand	15.61 MGD

FIRE FLOW REQUIREMENTS

The distribution system should be capable of supplying enough water to meet the fire flow requirements. The required fire flow is the rate of water flow, at a 20 psi[7] residual pressure and for a specific duration, that is needed to suppress a major fire in a specific location (AWWA, M31, 1998). The required fire flow rates are determined by the Insurance Service Office (ISO) using the Fire Suppression Rating Schedule (1980).

ISO is a non-profit association of insurance companies that compiles data that are used to establish rates for fire protection policies for both residential and commercial buildings. ISO typically estimates fire flow requirements at several locations within a community. The required fire flow is the rate of flow theoretically needed to successfully combat a major fire at a specific location. The ISO locations are selected according to their relative representation of the overall fire flow requirements of the community. Accordingly, only fire flow requirements for a small portion of the community are actually estimated by ISO. In October 2002, ISO determined that 22 of 37 locations tested in the city do not meet fire flow requirements (Table 2).

[5] Gallons per capita per day
[6] Million gallons per day
[7] Pounds per square inch

Table 2: Locations Not Meeting the Required Fire Flows

Test No.	Test Locations	Flow Tested GPM[8]	Pressure		Flow @ 20 Psi	
			Static Psi	Residual Psi	Available GPM	Required GPM
1	Wildwood Road @ Winthrop St	580	84	62	1000	1000/5000[9]
2	Court St @ Salem Street	1690	59	47	3200	3500
3	Harvard @ Main Street	1560	65	35	1900	3000
4	Mystic Ave @ James St	750	65	45	1200	2000
5	Main St @ Brooks Park	500	60	42	750	2250
6	Fellsway Nr. Riverside Ave	530	74	70	2200	1000/3500
7	Telsa Ave @ Winthrop St	1050	55	35	1400	2250
8	Fulton St.@ Ames Street	990	38	25	1200	1500
9	Central Ave @ Chipman Street	630	65	42	900	1500
10	Lawrence @ Governors Ave	1070	68	48	1700	3000
11	Fellsway @ Myrtle	530	63	43	800	1000/8000
12	Boston Ave @ Broadway	730	95	83	2000	2500
13	Winchester @ Newburn	750	89	70	1500	2500
14	Auburn Street Nr. High St	290	75	58	550	3000
15	High Street Nr. Allston Street	960	88	46	1200	3000
16	Mystic Ave @ Hicks Ave	1110	65	50	2000	3000/5500
17	E.Albion @ Willis	1280	100	68	2100	3000
18	Playstead Rd @ Roberts Rd	630	60	19	600	1500
19	Henry Street @ Joseph St.	770	76	45	1100	1500
20	Woburn @ Chandlem Rd	670	65	25	700	1500
21	Salem @ Fellsway	630	67	43	900	2500
22	Fells Ave @ Fellsway	710	58	44	1200	2500

WATER DISTRIBUTION SYSTEM MODELING

Water distribution system modeling involves use of a computer model simulating a distribution system to predict the performance of the system to solve various design and operational problems. Using the computer model to predict pressures and flows within a water distribution system, the system can be evaluated and system performance can be compared against design standards.

A schematic of a water distribution system consists of two entities: links and nodes. The pipes, pumps, and valves are represented as links, and the pipe intersection, demand points water sources, and end points are represented as nodes in the system schematic. The model data stored in the database are associated with the links and nodes. The pipe information such as length, diameter, roughness coefficient, and operational conditions are associated with the

[8] Gallons Per minute
[9] For Residential/Commercial Purpose

respective links. The nodes contain information about the elevation, grade line, tanks, and water demand.

The H_2OMAP Water Suite, modeling software, was used to assess the distribution system. H_2OMAP is provided by MWH Soft, allows development of multiple specific modeling scenarios for a water distribution model. The user can formulate and analyze numerous modeling alternatives based on different network facilities, demands, and operating scenarios. This helps in analyzing alternative recommendations and comparing the best alternatives.

In 2002, CDM an engineering consulting company developed a hydraulic model to evaluate Medford's water distribution system. The city made improvements to its distribution system based on recommendations from the previous evaluations and according to its need. All pipes that were rehabilitated were replaced with ductile iron (DI) pipe with cement mortar lining.

The same hydraulic model used by CDM was imported in the H_2OMAP and upgrades to the distribution system were added to develop an up-to-date model. Upgrades were added to the previous model by changing the diameter and the roughness coefficients (C-value) of the pipes upgraded. For ductile iron (DI) pipes with mortar lining used for water, the C-values range is 100-140 (Mays, 2000). The C-values for upgraded pipes were assumed using this range and considering minor losses. Also, Medford has installed two new pressure reducing valves (PRV) in the distribution system, and these were included in the upgraded model.

HYDRAULIC TESTS AND MEASUREMENTS

The accuracy of a hydraulic model depends on how well it has been calibrated. Therefore, the hydraulic field data used for calibration must be accurate.

Fire Hydrant flow tests are performed in the field to obtain data on pressures for a distribution system under static conditions (no water flowing from hydrants) and stressed conditions (flowing the hydrants), and can be used in conjunction with the hydraulic model to calibrate parameters such as pipe roughness.

Two or more hydrants are required to perform a fire hydrant flow test. One hydrant is identified as the gauge hydrant (always closed), where all pressure measurements are taken. The other hydrant is identified as the flow hydrant. When flow hydrant is closed, referred to as "static conditions", the pressure at the gauge hydrant is called as the **static pressure**. When one or more of the flow hydrants are open, referred to as "flowed conditions", the pressure at the gauge hydrant is called the **residual pressure** (Figure.2). (Haestad et al, 2003)

Figure 2: Gauge Hydrant and Flow Hydrant

A total of 20 fire hydrant flow tests were performed throughout the city to obtain pressure and flow data for calibration of the hydraulic model. The gauges used for field measurements were checked for calibration before and after the tests. PRVs were closed while performing the test to limit water coming from the high-pressure zone into the low-pressure zone.

The test locations were selected according to the following criteria:

- Spread throughout the distribution system.
- Significant distance from the known boundary heads (meter connections).
- Close proximity to areas of improvements.
- Areas of low fire flow as per the ISO fire flow requirement list (Table 2).
- Minimum inconvenience to residents and businesses.

Table 3 summarizes results of the fire hydrant flow tests performed in March/April 2005.

Table 3: Summary of Fire Flow Tests

Test No.	Locations	Static Pressure (psi)	Residual Pressure (psi)	Drop (psi)	Flow (gpm)
1	Main Street @ Harvard St	62	48	14	1346
2	Telsa Ave @ Winthrop St	56	38	18	1177
3	Boston Ave @ Broadway St	100	59	41	501
4	Joseph St & Henry St	80	35	45	803
5	Cotting St @ Lyman Ave	67	47	20	813
6	High St @ Playstead Rd	67	34	33	1736
7	Playstead Rd @ Roberts Rd	64	33	31	856
8	Sagamore St & Oak Ridge Rd	60	42	18	584
9	Central & Sheridan	70	56	14	1000
10	Winthrop Street @ Wildwood Rd	85	28	57	671
11	Lawrence & Governors	90	70	20	1434
12	Fulton St & Baxter St	42	26	16	956
13	Fulton St & Ames St	39	31	8	761
14	Park Ave @ Benmore St	43	33	10	1530
15	Hickory Ave & Fells Ave	41	30	11	1595
16	Court St. near Salem St.	65	51	14	1718
17	Salem St & Fellsway	68	43	25	741
18	Fells @ Myrtle	71	64	7	506
19	Corporation Way & Second	69	59	10	1725
20	Blake near Commercial	72	60	12	2388

CALIBRATING THE MODEL

Calibration is the process of comparing field data to the modeling results and, if required, making changes to the parameters describing the system until the model-predicted results reasonably agree with field data under all operating conditions. The parameters required to be adjusted for calibration may include system demands, roughness coefficient of pipes, pump operating characteristics, and other model attributes that affect simulation results.

Demands were assigned to each node in the model for calibration. Average daily demand was broken down and distributed equally in gpm among all the nodes in a pressure zone based upon MWRA metering information for each zone. By multiplying demands by a peaking factor or ratio, it was possible to analyze the performance of the system under existing and estimated future maximum day and peak hour demands.

The roughness coefficient (C-value), a component of Hazen-Williams formula for computing headloss through a pipe, is a relative measure of the hydraulic capacity of a water main. A high C-value means smoother pipe (with higher carrying capacity). For calibrating the model, C-values for pipes are estimated based on trial and error methods.

Boundary conditions required for calibration of the model are the hydraulic grade lines (HGLs) at the MWRA meters. These conditions are required input to the model during simulation of a particular fire flow test. This data was obtained from MWRA for the particular time and day of the test, and were modified to balance the flow from all the meters.

The Doonan Street Pump Station is the only booster pump station in the distribution system. The pump settings used in the model were the same as that of the previous model. The head raised by the Doonan Street pump is 25 feet.

CALIBRATION METHOD

A steady state simulation was performed for each of 20 fire flow test locations. The steady state simulation was done by creating scenarios for both static and residual conditions in the model for each of the 20 fire flow tests. The static and residual pressure condition scenarios have the same pipe sets and boundary conditions but different demand sets in the model. The static condition scenario has the average daily flow demand, and the residual condition scenario has the average daily flow plus an additional demand. This additional demand is the flow obtained at the time of the fire flow test at the flowed hydrant, and is assigned to the node representing the flowed hydrant in that scenario.

The static condition scenario for a test location is first checked to see if it predicts the pressure observed in the field. Changes are made in the model to simulate the static pressure, and then the residual condition scenario is checked to see if it predicts the pressure observed in the field. Accordingly, the pipe roughness coefficients are adjusted within acceptable limits so that it simulates the pressures observed in the field. Thus that location is considered to be simulated for static and residual condition scenario. Similarly, the remaining scenarios are simulated following the same method. During calibration of the model all the PRVs in the model were closed as the PRVs in the water distribution system had been closed while performing the fire flow test.

CALIBRATION ISSUE

There were five locations where steady state simulations couldn’t be performed by changing the C-values within acceptable limits. Trying various alternatives led to the possibility of a closed valve in the exiting distribution system. Medford Water Department inspected the locations and found a total of eight closed valves for the locations identified. These valves were kept closed in the model for calibration.

CALIBRATION RESULTS

The model was calibrated using the procedure described in the calibration method section. At this time, there are no universally accepted criteria for calibration of distribution system model (AWWA, 2005). For this study, the model is considered calibrated if predicted pressure drops are within +/- 10 percent of the observed pressures in the field. The calibrated model results are shown in Figure 3.

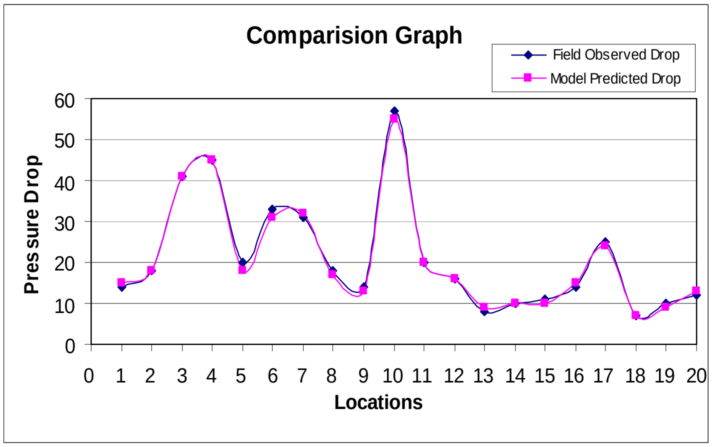

Figure 3: Calibration Results

ANALYSIS CRITERIA

The calibrated model was further used to analyze the water distribution system. The two criteria used for analyzing the water distribution system are:

- Providing peak hour demand while maintaining a minimum pressure of 35 psi within the entire system (Peak Hour Criteria).
- Providing a maximum day demand along with any one fire flow requirement while maintaining a minimum of 20 psi within the entire system (Maximum Day Demand).

CONCLUSIONS

Analysis of the calibrated model of the City of Medford's current water distribution system showed that the City's recent attempt to improve their water mains to meet their water demands has helped the water distribution system around the locations of upgrades.

Although there has been some improvement, the available fire flows for 19 out of 37 locations surveyed by ISO (2002) were still unable to meet the required fire flows. Also, under peak hour criteria, some areas in the northwest and many areas in the northeast of Medford were found to be below the pressure criteria of 35 psi.

For the locations failing to satisfy the criteria, several alternative upgrade scenarios were attempted in the model to determine the most appropriate improvement for the system. The recommendations are divided in two phases. The areas of low available fire flow that require immediate attention are included in Phase I recommendations. The Phase I recommendations are prioritized to provide maximum benefit to most of the distribution system. The priority list was made after trying several scenarios in the model. Phase II includes recommendations in locations that would further aid in improving the distribution system to meet the fire flow requirement and peak hour demand. There were also numerous closed/broken valves found in the distribution system during this study. The city should exercise valves with their annual unidirectional flushing program to help eliminate presence of closed/ broken valves.

A total cost of Phase I and Phase II recommendations is approximately 25 million dollars (US). Table 4 shows the model-predicted available fire flows after completion of the Phase I and Phase II improvements for the locations that did not meet the required fire flow as per ISO. The table shows that the model-predicted available fire flows after the completion of these improvements, meet the required fire flows at 20 psi residual pressure. Therefore, the city would be in compliance with the fire flows required by ISO.

Since the City of Medford's population has been decreasing gradually since 1960, for this study the fire flows required by ISO in the year 2025 are considered the same as that for 2002. Therefore, by executing Phase I and Phase II recommendations over the next 20 years, the city would be able to meet the fire flow criteria required by ISO. This would reduce the house insurance fees paid by the residents, and the water distribution system would be adequate in meeting its water demands as well as its fire-fighting capacity.

Table 4: Available Fire Flows after Phase I and Phase II Improvements

Test no.	**Test Locations**	**Flow @ 20 psi (GPM)**		
		Model Current Available after Calibration	**ISO Required**	**Model Available in future after Improvements**
1	Boston Ave @ Broadway	451	2500	**2418**
2	Central Ave @ Chipman Street	978	1500	**4248**
3	Court St @ Salem Street	2816	3500	**7299**
4	E.Albion @ Willis	1193	3000	**4738**
5	Fellsway @ Myrtle	924	1000/8000	**5987**
6	Fulton St.@ Ames Street	963	1500	**2979**
7	Harvard @ Main Street	2083	3000	**4124**
8	Henry Street @ Joseph St.	771	1500	**4043**
9	Main St @ Brooks Park	948	2250	**4926**
10	Mystic Ave @ Hicks Ave	1775	3000/5500	**3785**
11	Mystic Ave @ James St	660	2000	**2474**
12	Auburn Street Nr. High St	1134	3000	**3682**
13	Fellsway Nr. Riverside Ave	1912	1000/3500	**12549**
14	High Street Nr. Allston Street	1116	3000	**6428**
15	Playstead Rd @ Roberts Rd	1006	1500	**4461**
16	Salem @ Fellsway	1363	2500	**4534**
17	Telsa Ave @ Winthrop St	668	2250	**3539**
18	Wildwood Road @ Winthrop St	617	1000/5000	**5266**
19	Winchester @ Newburn	857	2500	**4135**

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