Exposure to Wells G and H in Woburn, Massachusetts

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This contract was prepared in fulfillment of an agreement with the Massachusetts Health Research Institute, Inc. (MHRI). This agreement is part of a Cooperative Agreement among the Federal Centers for Disease Control, the Massachusetts Department of Public Health, and MHRI to study the effects of enviornmental exposure to various chemicals on reproductive outcomes in Woburn.

SUMMARY

In May of 1979, the Massachusetts Department of Environmental Quality Engineering (DEQE) discovered that Wells G and H, two public drinking water wells in Woburn, Massachusetts, were contaminated with toxic chemicals. These wells were then shut off.

Subsequent studies of the health of the people of Woburn have indicated that the city had a higher level of childhood illness than would normally be expected. Research is currently being undertaken to determine the rate of adverse reproductive outcomes within Woburn, and to test associations between these outcomes and exposure to environmental contaminants, including the water from Wells G and H during the periods of their operation. This report presents the calculation of this exposure as a function both of roughly fifty hydraulically distinct neighborhoods within Woburn and of the 114 months of Wells' G and H operation.

The method used to calculate this exposure to water from the wells begins with a computer model of the water distribution system that was developed by the author under a previous contract with DEQE. This Woburn water distribution model was applied to the various pumping and water use configurations that occurred during each month that Wells G and H were in operation. The results of these calculations were then individually analyzed with a hydraulic mixing model to calculate the mixture of water supplied to each neighborhood. Finally, the resulting mixtures were combined in proportion to the period of their occurrence during each month to provide a monthly average exposure index for each neighborhood and each month. These indices were also summed to determine the cumulative exposure.

The validity and error levels of the distribution and mixing models were analyzed by comparing computer predictions of fluoride concentration distributions in both San Jose, California and Woburn with concentrations measured during field tests. The locations of the boundary between the zones with and without the fluoride tracer were predicted within one pipe junction of where they were observed.

The root-mean-square differences between predicted and observed dilutions were roughly thirty percent.

The levels of exposure to water from Wells G and H were found to vary widely as is shown by Figures 10 – 15. Typically the neighborhoods south and west of the center of the city, Main Street and Montvale Avenue, received no or very little water from Wells G and H. The neighborhoods of east Woburn along and near Washington Street received water mostly from Wells G and H whenever those wells were pumping. The mixture zone between the two water sources ran along, or just to the east of, Main Street.

I. Introduction

In May of 1979 the Massachusetts Department of Environmental Quality Engineering discovered that Wells G and H in Woburn, Massachusetts were contaminated with toxic chemicals. These wells were shut off and have not been used for water supply since then, but they had been in service for 2995.5 days since their installation in 1964. The rest of the city's wells were not contaminated and continue in operation. The Metropolitan District Commission supplied the water required to replace the water that had been supplied by the two wells.

Various studies (7,8,9) of the health of the people of Woburn indicate that part of the city had a higher incidence of certain childhood illnesses, including lymphocytic leukemia, than would normally be expected. The affected part of Woburn roughly coincided with the area served by the two contaminated wells. The water distribution system of Woburn was analyzed by Helen A. Waldorf and Robert K. Cleary of the New England Interstate Water Pollution Control Commission. Based on their 1984 report (10), a 1986 journal article (2) by Lagakos, Wessen, and Zelen has reported that the rates of childhood illness have "a statistically significant positive association" with the use of water from the two contaminated wells. A second water distribution analysis (3), made by the author to evaluate and complement the study of Waldorf and Cleary, concurred with their overall assessment.

At present the Centers for Disease Control, the Massachusetts Department of Public Health (MDPH) and the Massachusetts Health Research Institute (MHRI) are jointly working under a Cooperative Agreement to test statistical correlations between environmental exposure to various chemicals and reproductive outcomes in Woburn. Various media (air, water, soil) in Woburn are known to be contaminated, and so exposure through all these media will be examined as part of this Cooperative Agreement. The water from Wells G and H is one pathway of this exposure. Thus the calculation of the degree of exposure to contaminated water from Wells G and H is needed for this study. The Massachusetts Health Research Institute has contracted with the author for the performance of that work. This report presents the computer model of exposure to water from Wells G and H.

The ideal description of exposure to water from Wells G and H is the determination of the concentration history of each of the various hazardous chemicals in the water delivered to each residence during the active lifetime of the wells. First, the history of the concentration of each chemical at the two wells must be described. Although hydrogeologic investigations and groundwater quality evaluations (1,6) have determined some characteristics of the groundwater contaminant plumes that supplied water to Wells G and H, the wells' chemical history data are limited. The only measurements of contaminant concentrations of the well water were those leading to the shutdown of the wells. This report does not address this issue, but rather assumes that the wells were contaminated whenever they were pumping. The second part of the exposure description is the determination of the history of the distribution of the water from Wells G and H to describe the amount of that water used by every residence in Woburn. This report presents a study of G and H exposure using the author's water distribution model to calculate exposure in greater detail than was presented in the author's previous report (3).

That report, "Water Distribution in Woburn, Massachusetts," only presented flow patterns during twelve characteristic months, with each pattern dividing Woburn into three zones: Zone A with no G and H Water, Zone B with G and H water, and Zone C with some mixture of G and H water and water from the other wells. In the present study the author's water distribution models for the 1964 – 1969 pipe network and the 1970 – 1979 pipe network are applied as before to obtain water distributions for each month of the exposure period. An additional computer program, which accounts for the mixing of water from Wells G and H and the other Woburn wells during each month, is used to calculate an "exposure index" for over fifty hydraulically different neighborhoods within Woburn. This exposure index is the product of the fraction of the month when any contaminated water reached a particular neighborhood and, during that period of the month, the fraction of the water delivered to that neighborhood which came from the contaminated wells. For example if, during half of June, one third of the water at node 40 came from Wells G and H, then the exposure index at node 40 for June would be one sixth.

Since this report is founded on the author's previous report, that report is referenced often herein. Readers interested in the details of the water distribution model are referred to that report (3).

II. <u>Review of Woburn Water Distribution Model</u>

In general the Woburn water supply system takes water pumped from the ground at the City's wells and delivers it through a pipe network to the residential and business consumers of water. In order to deliver the amounts of water needed by the consumers, the system's operators use pump control valves and water storage tanks and reservoirs to regulate the water distribution. This section of the report describes this water supply system through the use of computer models. Since this study is founded on the author's previous report, "Water Distribution in Woburn, Massachusetts," that report is referenced often herein. Readers interested in the details of the water distribution model are referred to that report (3).

IIa. Woburn Water System Data

During the 1964 – 1979 period when Wells G and H were in service, the Woburn water pipe network changed very little. In 1970, however, some growth occurred in northeast Woburn and so two separate computer models of the pipe network were needed, one for the 1964-1969 period and one for the 1970-1979 period. Each model is a simplified description of the pipe network. The simplification of the networks was done to reduce the computer time needed for the analysis. Figures 1 and 2 show these simplified pipe networks.

The principal simplification of the pipe networks was the elimination of pipes that were not part of pipe loops. The users' water demands of the omitted "dead end" pipes were assumed to occur at the nearest pipe junction (node) of the remaining "looped" pipes. A second simplification was the elimination of small pipes whose carrying capacity was less than one-hundredth of that of larger pipes connecting the same pipe junctions. Finally, equivalent lengths of pipe were used to simplify cases where two different diameters were found between junctions and also where a number of small pipes were located in parallel. These simplifications did not appreciably change the results of the computer analysis, and they did significantly reduce the computer time used in finding the water distributions.

The data needed to present the principal water pipes as input for the computer models are given mainly in Table 1. This table gives a detailed list of these pipes' ages, types, dimensions, locations, and interconnections. While this list was well documented (3), the hydraulic roughness of the pipes was not. Therefore data (3) from 1983 pressure tests and fire hydrants, done for the ISO Commercial Risk Services Company, were used to "adjust" the pipe roughness values. This adjustment was a part of the calibration process of the computer models. That process is explained later in section IIb of the report.

The City of Woburn does not have water meters for all its water consumers and did not preserve the 1964 – 1979 readings of the meters it did use. Residences are charged a fixed annual fee for water, while large commercial and industrial users have meters that are read twice each year. Meter readings in 1984 accounted for 21 percent of the water supplied. In order to estimate the residential water use, an average water consumption of 370 gallons per day per residence was combined with the addresses of the residential consumers. Although there was some evidence (3) of significant leakage flows, because of their uncertain location no attempt was made to include the spatial distribution of leakage in modeling the user demand distribution. Thus the water bills of 1984 were used to prepare a street by street distribution of water consumption. This distribution was then simplified by subdividing Woburn into nearly fifty user demand areas with each corresponding to a representative water supply pipe junction (node) in its area. The boundary between two user areas was placed in the middle of the pipe connecting the two neighboring pipe junctions. Thus each user's residence was roughly assigned to the pipe junction from which its water came. Table 2 gives the street list for each user area and Figure 3 relates the user demand areas to the pipe network and the principal streets of Woburn. The locations of wells, reservoirs, and non-residential pipe junctions are other nodes which are also shown in this figure.

Although Table 2 is the principal description of the user demand areas, the study of adverse reproductive outcomes will locate residences in Woburn through geocodes, a numerical system of geographic location. Such numerical systems also permit computer graphics presentation of the exposure results. Since the following coding of the user demand areas is only approximate, the street lists of Table 2 should be used to determine the demand area of any particular residence.

The author has obtained through the University of Massachusetts Computing Center the numeric codes assigned by the U.S. Census Bureau to describe Woburn. In general these codes are composed of polygons (multi-sided geometric areas) representing the shapes of the states, counties, towns, and Census tracts. These geometric data are presented in the Dual Independent Map Encoding (DIME) format in Tables 3 and 4. This DIME format is commonly used for cartographic data files. Each data line in the tables describes a straight-line segment of the boundary between two areas identified by state, county, town, and Census tract. In this system Massachusetts is 25, Middlesex County is 017, and Woburn is 270, and these are assigned here as a part of the numeric codes for each line in the maps of the user demand areas. The usual Census tract codes have been replaced by user demand area codes. (Note that, because of the input format of the graphics program, 100 has been added to the number of the user demand areas in Figure 3 in order to form the geocodes for these areas.) The straight-line segments of the boundaries between the user demand areas are defined in the tables by the coordinates of their endpoints. The vertical (North-South) coordinate of each point is its latitude in degrees and ten-thousandths of a degree. The corresponding horizontal (East-West) coordinate is a modified longitude in degrees and ten-thousandths of a degree. The longitude modification is a change of reference site from Greenwich, England to somewhere in Iceland. Figures 4 and 5 are computer graphic representations of these DIME format maps of the 1964 – 1969 and 1970 – 1979 user demand areas. The exposure results presented graphically later in this report are superimposed on these base maps of the user demand areas.

An example of description of the straight-line segments of the boundaries between user demand areas is given by the following explanation of the first line in Table 3. The first demand area is identified by the state, county, city, and demand area values as “25 17270 101.” Next along the line, the second user demand area values as “025 17270 103.” The two endpoints of the line segment are identified by the coordinates described above, given in the next position along the line by the two pairs of values, “424535 533884” and “424612 53382.” The rest of the line gives two identifiers which were chosen by the author to be zero and a line counter. The first six lines of Table 3, taken together, describe the entire boundary of the first user demand area. That area is shown as # 1 in Figure 3 and as area # 101 in Figures 4 and 5.

In addition to water pipes and consumers, there are also reservoirs and pumps in the Woburn water distribution system. While the pipes are full of water except for the rare occasions when there is a local pipe failure, the storage reservoir have regular emptying and filling cycles. This cyclic variation of the reservoirs’ water elevations is due to the nature of the user demand. The people of Woburn use less water at night since most of them are asleep and they use more water in the morning when they bathe and wash clothes. Industrial demand is also heaviest during the day. An examination of the water level records for the reservoirs show that the maximum and minimum water demands are roughly 20 percent above and below the daily average demand, and that the maximum, average, and minimum demand periods are roughly of equal duration. These cyclic variations were well documented were well documented by the water level records (3) of the reservoirs and are included in the computer models by applying the distribution model to the maximum, average, and minimum demand conditions and then averaging the resulting exposures.

During the 1964 – 1979 period, there were eight well pumps and two significant booster pumps in the Woburn water system. As Figure 1 shows, Wells A2, B, C2, and D are clustered near the Horn Pond Reservoir. Well F is located along the pipe that passes west of Horn Pond. Well E is on Lexington Street just east of Cambridge Road. Wells G and H are off Salem Street near Washington Street, in east Woburn. The Horn Pond wells were controlled by throttle valves so that the pump operators could get the desired flow rates, while these wells' operating pressure was set by the nearby Horn Pond reservoir. Therefore the Horn Pond pumps were characterized simply by their flowrate. The other pumps were defined by their characteristic curves which were given in the previous report (3). All of these pumps were metered, thereby providing the data needed to document their pumping histories.

The pumping history of the 1964 – 1979 period was developed by examining the daily pumping records for all days when either wells G or H were pumping. The number of days each month that wells E, G, and H worked in their various combinations were calculated based on the hours pumped during each day of that month. Well E was included since the status of well E caused significant differences in the flow pattern in the water system. The individual pumping histories of the other wells did not affect the resulting distribution patterns due to their proximity to the Horn Pond reservoir. Pumping rates for each month were calculated from the volume of water and hours pumped. The monthly average flow rate of the Horn Pond well group, A2, B, C2, D, and well F was also calculated for each month. Finally, the total monthly water supply and the percentage of that supply that came from wells G and H were determined from the daily pumping records. This pumping history data is given in Table 5.

IIb. Computer Models of the Water Distribution

The analysis of a water distribution system is done by applying the basic principles of the conservation of the mass and energy to the water flowing through the system. The mass conservation principle is applied by assuming that the pipes do not leak along their lengths and that the water users take their water out of the system only at the pipe junctions. Water enters the system at the nodes corresponding to the wells and reservoirs. Thus the net flow rate into each user demand node must equal the user demand, Q_d, of that pipe junction. In most analyses the user demands are known and the flow rates,

Q_I, in the pipes connected to each demand node are the unknowns to be determined by the analysis. Mass conservation for each demand area is given by an equation of the form,

$$Q_1 + Q_2 + Q_3 = Q_d. \qquad (1)$$

The energy conservation principal is expressed in terms of height, usually referred to as "head." Potential energy is described by the elevation, Z, of the centerline of the pipe above mean sea level. The kinetic energy per unit weight is given by the square of the flow velocity divided by twice the acceleration of gravity, $V^2/2g$. The pressure energy per unit weight is given by P/gamma, where P is the pressure and gamma is the specific weight of the water. All these three kinds of energy are combined to form H, the "total head" or mechanical energy per unit weight by the equation,

$$H = Z + V^2/2g + P/gamma. \qquad (2)$$

The energy principal is applied to all the pipes of the network by requiring that the energy lost to friction, h_L, is the same as the energy differences between the junctions at the upstream and downstream ends of each pipe, as shown by equations of the form,

$$h_L = H_1 - H_2. \qquad (3)$$

This energy lost to friction can be calculated with one of the various empirical formulas that relate the loss to the flow rate through the pipe, the length and diameter of the pipe, and the roughness of the inner wall of the pipe. The formula used here is the Hazen-Williams equation,

$$h_L = 4.73\, L\, Q^n\, (C^n\, D^m), \qquad (4)$$

where L is the length of the pipe, D is the diameter of the pipe, n is 1.852, and m is 4.87.
A corresponding energy analysis describes how the well pumps and reservoirs supply the total head that drives the water into the pipe network.

The result is a large number of linear and non-linear equations which must be organized and solved to determine the flow rates through each pipe and the total head at each pipe junction. Table 6 summarizes the variables needed for this analysis and gives typical values and error levels for the data used in this study. The two mathematical methods commonly used to do this are the successive linear approximation method and the Newton-Raphson Method. More detail on the theory of water distribution system analysis can be found in elementary fluid mechanics textbooks and in Analysis of Flow in Pipe Networks by Roland W. Jeppson (4).

The computer program used for the analysis of the Woburn water distribution system is called NETWK. It was developed by Professor Roland W. Jeppson of Utah State University in association with the consulting engineering firm, CH2M-Hill of Corvallis, Oregon. The program is used by the author under a license from that firm.

The computer modeling of the water system began with a 1983-4 calibration process, comparing the 1984 model with a set of 1983 ISO data and other data for the water system on the day of those ISO field tests (3). The initial model had a total user demand of 4,000 gallons per minute and the same roughness coefficient, C – 80, for every pipe. This initial model was used to calculate the flow pattern in the water system, and then a comparison between the supply and demand flows of this computer model and the 1984 flow calibration data was made. The 1984 user demand estimate totaled only 4,000 gpm while the 1983 supply from the city's wells and the MDC, combined with reservoir outflow, gave a total supply of 5,600 gpm. This excess supply indicated that an "adjustment" should be made through the use of a scaling factor, 1.4, for the total water demand. A second adjustment was made by comparing the total head (potential energy per unit weight) of the computer model with the total head calculated from the substantial data set of fire hydrant pressures supplied by the ISO Commercial Risk Services Company. This adjustment changed the pipe roughness C values to a set of C values which varied from 40 for some older pipes to 120 for the newer ones. The error level of this ISO calibration process is obtained by comparing the total head distribution of the ISO measurements with that of the computer model after all the "adjustments" to user demand and pipe roughness were made. The average head difference of 28 data points and model values for total head was 0.9 feet, while the root-mean-square head difference was 6.2 feet.

The computer model of the 1983 – 1984 water system was field tested in 1985 to determine its validity and accuracy (3). Two different model predictions were checked, 1) the pressure distribution near Salem and Washington streets when a hydrant near that intersection was flowing and, 2) the pressure and fluoride distributions throughout Woburn when no fire hydrants were flowing. An assumption of the computer predictions was that the operation of the water system on the day of the field test would be typical of normal operation, but such was not the case. Therefore a re-prediction was made to correspond to that day's unusual operating conditions. Good agreement was found between the 16 field measurements and the computer model re-prediction. The error levels of the total heads have a mean value of 0.1 foot and a root-mean-square value of 7.5 feet. More details of the pressure validation analysis is available in the previous report (3). The fluoride distribution prediction and measurements are more descriptive of the distribution of water from Wells G and H. This fluoride validation is discussed further in the next section of this report.

The 1983 – 1985 water distribution model was next modified to produce models of the water system during the two periods, 1964 – 1969 and 1970 – 1979, when the contaminated wells were in service. User demand areas and pipes were deleted or changed to reflect the history of the development of the city. These changes had a large effect on the northeast section of Woburn but not on the overall water supply system. The 1970 –1979 model was compared to ISO hydrant data from the years 1970, 1972, 1974, and 1975 to check the validity of the modified model (3). Similarly, the 1964 – 1969 model was compared to ISO data from 1965 and 1969. The mean pressure differences shown by these comparisons were small, 3.6 feet for 1970 – 1979 and 3.1 feet for 1964 – 1969, as was the root-mean-square value of 9.5 feet for 1970 – 1979, but the root-mean-square value of 16.3 feet for 1964 – 1969 was high. Since the operating conditions during these tests were unknown, corrective action lacked direction and so no changes were made.

The report (3), "Water Distribution in Woburn, Massachusetts," presented the application of the computer models reviewed in this section to produce thirty-six exemplary flow patterns. Eighteen patterns showed water distributions with well E on and eighteen with it off. Each group was made up of flows for maximum, average, and minimum percentages of flow from wells G and H, for maximum, average, and minimum values of daily user demand, and for both the 1964 – 1969 and 1970 – 1979 periods. That report did not include the calculation of the mixing which occurred at some pipe junctions but simply divided Woburn into three zones for each flow pattern: Zone A with no G or H water, Zone B with G and H water, and Zone C with some undetermined mixture of G and H water and water from the other wells. In sections III and IV of this report, the determination of the Zone C mixing is considered.

III. Wells G and H Exposure Model and its Validity

The computer program for the mixing of the water from wells G and H was first developed and used by the author as a part of the effort for a report (5), "The Great Oaks Water Distribution Study," prepared for the California Department of Health Services. This study of the Great Oaks Water Company's pipe network, wells and user demand areas followed the method of the previous Woburn study (3) by applying the NETWK computer program to analyze the flow patterns in that water district. The output of the NETWK water distribution program determined the flow rate in each pipe of the water system. Then the author's computer program for the mixing process was applied to these flow patterns.

The analysis of the contaminant movement and mixing in the water distribution is done by applying the principle of mass conservation to the mass of pollutant in the water system. The mixing process was applied to these flow patterns by assuming that the pipes' flow rates were not changed by the addition of small amounts of dissolved contaminants to the water. The pollutants were assumed to move through the pipes with the water without changing their concentrations, and at each pipe junction the inflows were assumed to mix completely due to the turbulent nature of the pipe flow. The mass conservation equation for this mixing at junctions has the form,

$$P_1 Q_1 + P_2 Q_2 = P_3 (Q_3 + Q_d), \qquad (5)$$

where P denotes the pollutant concentration, pipes 1 and 2 are inflow pipes to the junction, and pipe 3 is an outflow pipe from the junction. The consumers of water in each user demand area were assumed to get the mixed water of that node and all the outflow pipes from those pipe junctions were assumed to carry the mixed water to the farther points of the pipe network.

The spread of water from a particular well is determined by setting P =1.0 for that water source and P = 0.0 for the other sources. Then the computer program sequentially examines the inflows to the nodes downstream from the sources and applies equation 5 to calculate the outflow concentration from those nodes, going from node to node until all the user demand areas are analyzed.

In the present Woburn study, the pollutant mass conservation principle and these same assumptions are applied through the same computer program for the mixing process. Before looking at more details of the exposure calculations that apply the NETWK and mixing programs to the 1964 – 1979 distributions of water from Wells G and H, the field tests of the two previous studies are now examined to provide some insight into the validity and accuracy of these calculations.

IIIa. Great Oaks Validation Tests

In the Great Oaks study (5), the water distribution and mixing models were checked by using the models to predict the spatial distribution of the fluoride concentration that would result if fluoride with P = 2.00 parts per million were injected at Well 16, shown as GO 16 in Figure 6, and allowed to spread throughout the Great Oaks pipe network. This figure shows the predicted values of the fluoride levels based on the actual test's injection concentration of 1.51 ppm, and Table 6 shows both the original fluoride prediction and the prediction modified by scaling to the actual 1.51 ppm concentration. A field test of the prediction was then made by injecting fluoride at Well 16 and measuring the fluoride distribution that resulted. These fluoride concentrations are given in Figure 7 and also in Table 7.

While both the model and the field test had inaccuracies described in the Great Oaks report, it was clear that the computer models located the boundary between the Well 16 water and the water from the other wells improperly by one node at a few key locations. An error analysis of the predicted and observed concentrations given at the bottom of Table 7 shows a mean error of 0.03 ppm and a root-mean-square error level of 0.31. The large rms value is due to a few points near the Well 16 water's boundary with large errors. The error bands given in Table 7 show that 64 percent of the predictions were within 0.2 of the measured concentrations.

IIIb. Woburn Validation Study

In the previous Woburn water distribution study (3), a field test of the predicted pattern of fluoride concentrations was only compared qualitatively with the computer model's prediction. At that time mixing analysis was not included in the fluoride calculations. During this study the fluoride concentration prediction is re-examined by doing that mixing analysis. The 1985 fluoride source was the MDC connection on Montvale Avenue in east Woburn. Its fluoride concentration was 1.07 ppm while the other sources of water, Woburn's wells, had only 0.07 ppm.

The qualitative comparison of the prediction, Figure 8, and the field test results, Figure 9, shows that both divide Woburn into three zones, an east Woburn zone with MDC water (1.07 ppm), a southwest Woburn zone with water from the Woburn wells (0.07 ppm) and a northwest zone with a mixture of water from both sources. The prediction indicates that the boundary between the first two zones is located one node east of Main Street except at Mishawum Road and Eaton Street. The field test indicated that this boundary was along Main Street. A similar one node difference in location occurred between the MDC water and the mixed water in north Woburn.

The predicted and observed (two labs) values of the fluoride concentrations are also compared in Table 8. This time the mean error was 0.07 ppm and the rms error was 0.29 ppm. The error bands in Table 8 show that 72 percent of the predictions were within 0.2 of the observed values. These values and the other statistical analysis shown in Table 8 indicate an accuracy level nearly equal to that given by the Great Oaks validation.

Taken together the two field tests using the fluoride tracer demonstrate that the water distribution and mixing models can predict the location of the boundaries of the area receiving water from Wells G and

H within one node. The models can predict mixture concentrations with an average error within ten percent of the maximum concentration and a root-mean-scare error within thirty percent of that level. Large errors (100%) in the mixture concentrations occur at a few points near the fluoride boundary due to one node errors in locating the pipe junctions where mixing occurs, but nearly seventy percent of the predictions are within twenty percent of the measurements.

IIIc. Well G and H Exposure Study

In the present study of the exposure to water from Wells G and H, the existing water distribution models for the periods 1964 – 1969 and 1970 – 1979 are applied to obtain typical water distribution patterns for each month when the wells were pumping. The mixing program is applied to each pattern to calculate the fraction of the water supplied to each user demand area which came from the contaminated wells.

As was shown in the previous Woburn report (3), the flow patterns are not affected by different combinations of wells near Horn Pond, but different flow patterns are produced when Well E is on and when it is off. A typical month has periods with Well E on or off and also has three peaking factors (1.2, 1.0, 0.8) accounting for the maximum, average, and minimum water demands of the daily water-use-cycle. The monthly analysis must therefore account for each of these six conditions and requires six water distribution calculations and six applications of the mixing program. A small computer program was developed during this study to combine the six resulting mixtures for each month in proportion to their duration.

The result is an exposure index assigned to each user demand area during the months of the two exposure periods, 1964 – 1969 and 1970 – 1979, when the G and H wells were in operation. That exposure index is the product of the fraction of the time during the month when any contaminated water from Wells G and H reached the user area and the fraction of the water supplied to that user area which came from the contaminated wells. The units of this exposure index are months, with a maximum value of one month occurring if Well G is on all month and if the user demand area was supplied with Well

G's water during the entire month. Since this method of calculation of Well G and H exposure is the same as that applied to the fluoride mixing prediction, the resulting exposure indices should have the level of accuracy indicated by the fluoride field tests.

During some months, for example August and September of 1967, the six distributions needed for different peaking factors and Well E status were not enough. In these months, when Wells G and H were operated in different combinations, separate calculations were done for each combination and then either twelve or eighteen different results were combined to produce the monthly average exposure indices of those months.

Table 9 shows the monthly averaging process for May 1979 as an example of the combination process for the six distribution cases. The pumping conditions given in Table 5 and at the top of Table 9 show the fractions of this month that Wells E, G, and H were operating. Wells G and H were operating during 70 percent of the month. Well E was on all month. The six columns on the right in Table 9 give the fraction of the water that came from the contaminated wells during the parts of the month when the average, maximum, and minimum water demands occurred with Well E off or on. Since Well E was on all month, the monthly exposure is the average of the three exposures for the different peaking factors with Well E on, multiplied by 0.70. The column labeled EXPINDX presents the resulting monthly average exposure index for each user demand area for the month. The maximum index, 0.70 months, is found in the areas of east Woburn. An example of a smaller average exposure index, that for node 32, is given by the calculation,

$$(0.70)\ (0.124 + 0.067 + 0.180)\ /\ 3 = 0.087 \qquad (6)$$

IV. Exposure and Cumulative Exposure Results

The water distribution and mixing models were used to calculate the exposure indices for all the months when Wells G and H were pumping. The spatial patterns of the exposure distributions are difficult to understand from a list of the exposure values, and so Figures 10, 11, and 12 are presented to show the patterns typical of medium, broad, and small areas of exposure to water from Wells G and H during the 1964 – 1969 period. The exposure index values for 1964 – 1969 are given in Table 10. The initial results indicated that street lists of the previous report (3) for user demand areas 33 and 34 were incorrect and so these areas were changed to reflect the initial flow pattern.

In Figure 10 the geocode description of the user demand areas is the base upon which the exposure index results are presented. Different densities of cross-hatching show six ranges of values of this exposure and the areas without any cross-hatching give a seventh. The densities increase with increasing exposure. The five main exposure ranges are roughly equal in size, 0.20 months, and they give the high exposure pattern. In addition, two smaller ranges present an order of magnitude estimate of a trace range (0.010 to 0.001 months) and a near zero range (no cross-hatching). The exposures shown are those of June 1966, a month whose exposure pattern is typical of the median of the 1964 – 1969 period. The areas of east Woburn along Washington Street and just to the west of that street received G and H water nearly all that month. The areas of southwest Woburn received no G and H water and a band of user demand areas near Main Street received various mixtures of the G and H water and water from the Horn Pond wells.

A broad area of exposure is shown by the exposure pattern of October, 1967 (Figure 11). It is typical of the largest spread of the water from Wells G and H. During this month the mixture areas near Main Street received a higher fraction of their water from Wells G and H, and trace amounts of G and H water even reached the extreme southwest corner of Woburn. Only a small zone around Horn Pond was unaffected by the water from those two wells.

A small area of exposure is given by the exposure pattern of June, 1969. Thus Figure 12 is typical of the minimum spread of G and H water during the 1964 – 1969 period. During that June both the high exposure zone and the mixture zone were limited to the demand areas east of Main Street. Water from Wells G and H did not reach northwest Woburn during this month.

The spatial patterns of the exposure distributions of the 1970 – 1979 period are illustrated by Figures 13,14, and 15. These figures show patterns typical of medium, broad, and small areas of exposure to water from Wells G and H during that period. The exposure index values for 1970 – 1979 are given in Table 11. The water distribution model changed in 1970 due to the development of new housing, commerce, and industry, largely in northeast Woburn. This change increased the water demand in that part of the city and so decreased the spread of the G and H water to the rest of Woburn. This effect caused the main difference between the results of the periods 1964 – 1969 and 1970 – 1979.

The exposure pattern of March, 1979 is shown in Figure 13. Its medium exposure area is typical of the 1970 – 1979 period. The areas of east Woburn along Washington Street and just to the west of that street received G and H water nearly all that month. As in Figure 10, areas of southwest Woburn received no G and H water and a band of demand areas near Main Street received various mixtures of the G and H water and water from the Horn Pond wells. This pattern is quite similar to that of Figure 10.

Figure 14 presents the broad exposure pattern of the month of October, 1974. It is typical of the maximum spread of the water from Wells G and H during 1970 – 1979. While it is similar to the maximum pattern for 1964 – 1969, shown by Figure 11, in Figure 14 the trace amounts of G and H water do not reach into southwest Woburn.

The smallest zone of exposure for both the 1964 – 1969 and 1970 – 1979 periods is shown in Figure 15. That figure gives the exposure pattern for October, 1976. It shows peak exposures only in the areas along Washington Street that are near Salem and Montvale Avenues. During this month the mixing zone reaches both the northern and southern ends of Washington Street, and the zone free of exposure extends well to the east of Main Street.

The cumulative exposure for every month when Wells G or H were pumping was also calculated. This was done by adding the exposure index for each month to the cumulative exposure of the previous

month whenever Wells G or H were in operation. The resulting sum is the number of months of exposure prior to the end of the month whose cumulative exposure is being calculated.
The month of October, 1964 was special since as the first month it had no antecedent. In its case the cumulative exposure and the exposure index are equal. These results are presented in Tables 12 and 13. The cumulative exposure for the many months when neither Well G nor Well H was pumping is not listed in these tables since the cumulative exposure for any of those months is the same as that of the previous month in the tables.

Since the goal of this study is to examine the rate of adverse reproductive outcomes as a function of exposure to water from Wells G and H, some examples of the use of Tables 10, 11, 12, and 13 are included here. Assuming that a nine-month pregnancy began November 1, 1964 and ended July 31, 1965 and that the mother lived in user demand area (node) 66, Table 10 gives exposures of 0.47 and 0.50 months for the first two months of the pregnancy and zero (G and H both off) for the next seven months. Table 12 gives a cumulative exposure for the mother of 1.51 months, but also indicates (by subtraction) a cumulative exposure during the pregnancy of 0.97. If a five-month pregnancy of a mother living in node area 35 began March 1, 1976 and ended July 31, 1976, then the exposure values (Table 11) were 0.42, 0, 0, 0.61, and 0.97 months, while the cumulative exposure is 2.00 months. Finally, if a mother lived in user demand area 58 all her life and had children after 1981, then her cumulative exposure (Table 13) before her pregnancies was 64.08 months.

V. Conclusion

The purpose of this study of exposure to the water from Wells G and H in Woburn, Massachusetts is to describe when and where that water was delivered to the residences of Woburn. This result will then be compared with occurrences of selected adverse reproductive outcomes through the Health Outcomes Study.

Tables 10 and 11 report the principal results of this study. The water pipe network of the 1964 – 1969 period of operation of Wells G and H was used to divide the city into 52 hydraulically distinct neighborhoods, and the pipes of the 1970 – 1979 period were used to give 54 such neighborhoods. Since the wells pumped during 44 months of the 1960's period, Table 10 is a matrix of numbers between zero and one that indicate the fraction of the water, supplied to each user area, which came from Wells G and H during each of the 44 months. Table 11 presents this exposure index for the 54 user areas during the 70 months of the 1970 – 1979 period. These matrices demonstrate that areas 11, 17, 18, 19, 20, 21, 22, 30 and 31 did not receive a significant amount (0.01) during any month. At the other end of the exposure range, areas 39, 42, and 44 received all their water from Wells G and H whenever either of those wells was operating.

The accuracy of these exposure results was estimated by examining both the fluoride field test results and the ISO fire hydrant comparisons of total head data and computer model calculations. The fluoride tests show that the computer models for present-day water systems can only locate the fluoride boundary within a spatial error of one node, and so predicting the mixture concentrations in the user areas along that narrow boundary is a difficult task. Tables 7 and 8 indicate that the fluoride predictions had a root-mean-square error level of 30 percent due mainly to a few large errors near the boundary between the zones supplied by the two sources. This indicates that the exposure index values do not have the two significant digits reported in Tables 10 and 11, and that the trace levels shown in Figures 10 – 15 are only roughly valid. Further, the ISO comparisons in Section IIb demonstrate that the lack of historical data increases the differences between the computer model results and the actual field measurements.

However, even with this high error level, the low mean error and the error band analysis indicate that on average there is a connection between the models' predictions and the field observations. It is the author's opinion that a good estimate of the error level of the models is twenty to thirty percent. Thus the mixture region should only be divided into three sub-regions: 0.0 – 0.33, 0.34 – 0.67, 0.68 – 1.00.

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NOTE:

The Massachusetts Department of Public Health, Bureau of Environmental Health Assessment was unable to make the following figures and tables available via the internet.
Please call (617) 624-5757 to request photocopies of the original documents.

Figure 1: 1964-1969 Pipe network with pipe numbers and diameters
Figure 2: 1970-1979 Pipe network with pipe numbers and diameters
Figure 3: 1984 User Demand Areas
Figure 4: 1964-1969 User Demand Areas by Geocodes
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Figure 11: Large Exposure Area of 1964-69; October, 1969
Figure 12: Small Exposure Area of 1964-69: June, 1969
Figure 13: Typical Exposure Area of 1970-79: March, 1979
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Figure 15: Small Exposure Area of 1970-79: October, 1976

Table 3: 1964-1969 User Demand Areas by Geocodes
Table 4: 1970-1979 User Demand Areas by Geocodes
Table 5: Well Use and Pumping Rates and Total User Demand
Table 7: Great Oaks Flouride Validation Results
Table 8: Woburn Fluoride Validation Results
Table 9: Monthly Averaging Process
Table 10: 1964-1969 Exposure Index
Table 11: 1970-1979 Exposure Index
Table 12: 1964-1969 Cumulative Exposure Index
Table 13: 1970-1979 Cumulative Exposure Index

TABLE 1
1985 PRINCIPAL WATER PIPES IN WOBURN, MASSACHUSETTS

Street(s)	Length (ft.)	Diam. (in.)	Type*	Date Built	Age in 1985(yrs.)	Pipe No.	From Node	To Node
Russel and Liana	4200	6	CI	1915	70	1	4	1
Lexington, Maura and Samoset	5200	10	CI	1963	22	2	3	1
Lexington & Waltham	3700	12	CI	1959	26	3	4	3
Waltham & Zion Hill	700	10	CI	1959	26	4	3	2
Cambridge, Revere, and Whispering Hill	4600	12	AC	1962	23	5	4	5
Booster Pump at Cambridge and Russell	400	12	CI	1959	26	6	6	4
Cambridge from Lexington to Bedford	4800	6	CI	1921	64	7	7	6
Bedford from Cambridge to S. Bedford	2800	10	CI	1921	64	8	8	7
Lexington from Cambridge to Well E	3000	6	CI	1913	72	9	9	6
Garden and South Bedford	4500	12	CI	1919/38	66/47	10	9	8
Well E Connector	800	12	CI	1937	48	11	10	9
Lexington from Well E to Woburn Pkwy.	2600	6	CI	1913	72	12	9	11
Bedford and Kilby	7000	10	CI	1928	57	13	24	8
Cambridge from Russell to Well D	7200	12	CI	1959	26	14	12	6
Well D to Well F	5700	16	CI	1959	26	15	12	13
Water to Connector to Well F	3700	16	CI	1909	26	16	13	11
Connector to Well F	100	10	CI	1959	26	17	14	13
Well D to Well C	800	14	CI	-1900	85	18	12	15
Well C to Horn Pond Reservoir	500	16	CI	-1900	85	19	15	16
Well C to Wells A_2, B, C_2	200	16	CI	-1900	85	20	15	17
Lake and Arlington	6000	16	CI	1921	64	21	17	18
Pleasant from Woburn Pkwy. to	1300	16	CI	1916	69	22	11	18

* CI = Cast Iron
AC = Asbestos Cement

Street(s)	Length (ft.)	Diam. (in.)	Type*	Date Built	Age in 1985(yrs.)	Pipe No.	From Node	To Node
N. Warren								
Lake and Main to Fowle	4700	16	CI	1913	72	23	17	19
Main from Fowle to Green	900	16	CI	1914	71	24	19	20
Main from Green to Montvale	2000	16	CI	1914	71	25	20	21
Main from Montvale to Pleasant	300	16	CI	1914	71	26	21	22
Pleasant from N. Warren to Main	1300	16	CI	1916	69	27	18	22
Main from Montvale to Salem	900	16	CI	1914	71	28	22	23
Main from Salem to Kilby	1400	16	CI	1915	70	29	23	24
Main from Kilby to Clinton	1900	16	CI	1917	68	30	24	25
Main from Clinton to Wyman	700	16	CI	1917	68	31	25	26
Ellis	1700	16	CI	1959	26	32	11	27
N. Warren from Pleasant to Ellis	1100	10	CI	1910	75	33	18	27
Harrison and Winn to Pleasant	2100	16	CI	1959	26	34	22	27
N. Warren and Winn to Bedford	1750	20	CI	1959	26	35	27	28
Bedford and Hillside	1400	24	CI	1959	26	36	28	29
Kilby, Hart, and Wyman	3800	16	CI	1959	26	37	28	26
Fowle and Garfield to Green	1500	8	CI	1915/27	70/58	38	19	30
Green from Main to Garfield	1700	10	CI	1929	56	39	20	30
Montvale from Main to Auburn	1100	12	CI	1922	63	40	21	31
Auburn and Garfield to Green	3400	8	CI	1927	58	41	30	31
Montvale from Auburn to Bow	1900	12	CI	1922	63	42	31	32
Montvale from Bow to Wood	2200	12	CI	1922	63	43	33	32
Montvale from Wood to Green	1000	12	CI	1910	75	44	34	33
Green from Garfield to Montvale	4500	10	CI	1929	56	45	34	30
Montvale from Green to Central	1500	12	CI	1910	75	46	35	34
Montvale from Central to Washington	600	12	CI	1910	75	47	36	35
Montvale from Washington to MDC	100	12	CI	1975	10	48	37	36
Central and D Streets	3300	6	CI	1914	71	49	35	38
Washington from Montvale to D	2500	6	CI	1920	65	50	36	38
Washington from Montvale to Pine	1800	6	CI	1932	53	51	36	39
Central from Montvale to Pine	1300	12	CI	1975	10	52	35	39
Salem from Main to Bow	3400	10	CI	1920	65	53	23	40
Bow	2000	6	CI	1921	64	54	32	40
Salem from Bow to Wood	1500	10	CI	1920	65	55	40	41
Wood	2600	6	CI	1920	65	56	33	41

Street(s)	Length (ft.)	Diam. (in.)	Type*	Date Built	Age in 1985(yrs.)	Pipe No.	From Node	To Node
Salem from Wood to Pine	1200	10	CI	1920	65	57	42	41
Pine	3500	10	AC	1930	55	58	39	42
Washington from Pine to Cedar	3400	6	CI	1930	55	59	39	44
Salem from Pine to Wells G & H	1700	12	AC	1965	20	60	42	43
Salem and Cedar to Washington	1400	12	AC	1965	20	61	43	44
Wells G & H Connector	750	12	AC	1965	20	62	45	43
Clinton	800	6	CI	1928	57	63	25	46
Beach	3000	6	CI	1928	57	64	40	46
Eaton	1400	16	CI	1960	25	65	26	47
Mishawum from Clinton to Eaton	600	6	CI	1957	28	66	46	47
Mishawum from Eaton to Forest Pk.	600	16	CI	1960	25	67	47	48
Mishawum from Forest Pk. To Olympia	2500	16	CI	1960	25	68	48	49
Olympia from Mishawum to Wildwood	1000	16	CI	1960	25	69	49	50
Wildwood	5000	12	CI	1970	15	70	41	50
Olympia from Wildwood to Washington	3800	16	CI	1960	25	71	50	51
Washington from Cedar to Olympia	2000	12	AC	1965	20	72	44	51
Forest Pk. from Mishawum to Alfred	2800	16	AC	1970	15	73	48	52
Forest Pk. from Alfred to School	1100	16	AC	1970	15	74	52	53
School from Forest Pk. to Mishawum	1600	6	CI	1932	53	75	53	54
Mishawum from Olympia to School	1000	6	CI	1899	86	76	49	54
New Boston from School to New Industrial	1100	16	AC	1970	15	77	53	55
New Industrial	1800	12	AC	1971	14	78	55	56
Ryan	800	12	AC	1971	14	79	54	56
Mishawum from Ryan to Commerce	2500	16	CI	1978	7	80	56	57
Mishawum from Commerce to Washington	1100	24	CI	1973	12	81	58	57
Washington from Olympia to Mishawum	1600	16	CI	1973	12	82	51	58
Commerce Way	3200	20	CI	1973	12	83	57	59

Street(s)	Length (ft.)	Diam. (in.)	Type*	Date Built	Age in 1985(yrs.)	Pipe No.	From Node	To Node
Commonwealth Avenue	3700	10	AC	1977	8	84	59	60
Washington from Mishawum to Commonwealth	3300	6	CI	1920/38	65/47	85	58	60
New Boston from New Industrial to Merrimack	4100	16	AC	1970	15	86	55	61
Main from Wyman to Alfred	4100	16	CI	1917	68	87	26	62
Alfred	2900	6	CI	1931	54	88	52	62
Elm from main to West	1300	12	CI	1920	65	89	62	63
Elm from West to Main	1800	12	CI	1920	65	90	63	64
Main from Elm to Nichols	500	12	CI	1927	58	91	64	65
School from Main to Merrimac	700	6	CI	1924	61	92	64	66
School from Merrimac to New Boston	3700	6	CI	1932	53	93	53	66
Merrimac	4900	6	CI	1924	61	94	66	61
Nichols	1200	12	CI	1927	58	95	65	67
Webster	1500	12	CI	1927	58	96	67	68
Pearl and West	3000	6	CI	1916	69	97	63	68
Pool and Winter	2000	6	CI	1925	60	98	67	69
Mountain	2200	6	CI	1923	62	99	70	69
Main from Nichols to Mountain	2000	6	CI	1913	72	100	65	70

*

* CI = Cast Iron AC = Asbestos Cement

TABLE 2
1984 USER DEMAND AREAS, BASED ON WATER METER ADDRESSES AND THE STREET INDEX FOR POLLING PLACES

Node #	Addresses	# of Residences
1	Anna Road	30
	Canterbury Road	19
	Carroll Road	28
	Carson Road	16
	Cerqua Street	10
	Dix Road	37
	Dix Road Ext.	
	Douglas Green	
	Duren Avenue	45
	Exeter Drive	13
	Fortune Road	16
	Gayle Street	12
	Gettysburg Street	16
	Grant Street	10
	Hallmark Drive	19
	Hampshire Cr.	3
	Helen Drive	2
	Howard Court	6
	Johnson's Grant	
	Kendall's Mill	
	Kensington Avenue	10
	Kensington Drive	
	Liana Street	19
	Linda Street	5
	Lee Road	18
	Lexington Street, 310 to end	35
	Manomet Road	13
	Melo Road	11
	Michael's Green	
	Parliament Lane	22
	Penny Road	11
	Quail Run	
	Rich Road	27
	Robinson Road	50
	Roman Road	20

Node #	Addresses	# of Residences
	Russle Court	
	Russell Street, 206 to end	56
	Ryder Drive	2
	Sachem Road	8
	Samoset Road	45
	Sawmill Brook Way	
	Saw Mill Brook Way	
	Senator Road	17
	Seneca Road	18
	Squanto Road	20
	Stonewall Drive	11
	Strawberry Lane	3
	Tanners Circle	4
	Todd Road	10
	Vinebrook Way	
3	Arcadia Street	7
	Aspen Street	6
	Aspin Street	
	Bernard Road	25
	Glade Street	7
	Glenwood Avenue	27
	Grace Road	28
	Henderson Road	18
	Heritage Drive	23
	Janis Terrace	8
	Jean Road	5
	Lexington Street, 242 to 309	29
	Maura Drive	21
	Minchin Drive	26
	Morning Side Drive	8
	Morning Side Circle	6
	New Village Road	1
	Parker Street	16
	Ridgewood Lane	7
	Summit Street	5
	Waltham Street	43
	Waverly Road	31
4	Adams Circle	5
	Battle March Way	
	Bay Road	

Node #	Addresses	# of Residences
	Bay Street	6
	Belford Circle	11
	Brisco Road	15
	Brook Road	4
	Crescent Road	13
	Dawes Circle	9
	Freedom Road	10
	Gilda Circle	
	Independence Drive	59
	Kosciusko Street	10
	Lexington Street, 200 to 241	7
	Mathew Place	
	Minuteman Road	
	October Lane	
	Old Cambridge Road	2
	Old Lexington Road	
	Old Lexington Street	
	Otis Street	12
	Patriot road	5
	Pheasant Lane	12
	Prescott Way	7
	Revere Road	64
	Russell Street, 1 to 205	35
	Silver Mine Road	
	Silvermine Road	10
	Stevin Drive	4
	Sylvanus Wood Lane	34
	Tory Row	
	Whispering Hill Road	14
	Windsor Circle	
	Windsor Drive	
6	Cambridge Road, 60 to end	37
	Chapel Way	
	Country Club Road	48
	Crossman Road	6
	Crawford Drive	9
	Day Circle	53
	Flint Circle	
	Gately Drive	
	Glen Road	4

Node #	Addresses	# of Residences
	Hiawatha Road	39
	Indian Hill Road	30
	Larch Road	4
	Ledgewood Road	9
	Lexington Street, 145 to 199	10
	Locust Street, 101 to end	
	Lover Lane	
	Loves Lane	5
	Mayflower Road	35
	Pond Terrace	9
	Rehabilitation Road	101
	Surrey Circle	4
	Surrey Road	33
7	Bedford Road, 162 to end, 177 to end odd	198
	Cambridge Road, 1 to 59	130
	Churchill Road	14
	Downs Court	
	Kennedy Road	12
	Marlboro Road	63
	Princeton Road	6
8	Banner Drive	3
	Bamberg Drive	6
	Bedford Road, 34 to 160 even, 35 to 175 odd	46
	Bedford Terrace	2
	Bonnie Way	
	Brandt Drive	16
	Bruce Road	11
	Burlington Street, 71 to end	
	Cassidy Drive	10
	Doherty Place	3
	Elijah Street	22
	Houghton Street, 1 to 30	
	Jaycin Circle	5
	Katie Lane	
	Morrow Drive	8
	Oak Knoll Circle	
	Oak Knoll Drive	
	Quimby Avenue	32
	Rag Rock Drive	16
	Rock Street	14

Node #	Addresses	# of Residences
	Sheridan Street	36
	Sheilds Street	
	Shields Street	10
	South Bedford Street	23
	Thistle Road, 18 to end	8
	Thornton Street	13
	Willow Street, 48 to end	
9	Akerson Road	9
	Akeson Road	
	Acorn Street	4
	Brookland Road	3
	Bruno Terrace	10
	Burlington Street, 1 to 70	
	Cannon Road	3
	Clifford Terrace	6
	Columbus Road	24
	Foley Road	3
	Gangi Terrace	5
	Garden Heights Avenue	7
	Garden Drive	
	Garden Street	24
	Harrison Avenue, 80 to end	21
	Houghton Street, 31 to end	
	Kennedy Park	13
	Laurence Road	7
	Lexington Street, 1 to 144	72
	Locus Circle	
	Locust Street, 1 to 100	24
	Mawn Avenue	
	Mawn Drive	2
	Mount Ida Street	8
	Totman Drive	89
	Willow Street, 1 to 47	
11	Adams Drive	4
	Arlington Road, 40 to even, 37 to 81 odd	34
	Bacon Street	6
	Beacon Street	49
	Brandon Court	
	Ellis Street, 1 to 37	18
	Evans Road	

Node #	Addresses	# of Residences
	Evans Street	
	Geary Drive	2
	Harrison Avenue, 50 to 79	17
	Millet Street	1
	Millett Street	
	Oak Street	5
	Pleasant Street, 94 to end	45
	Reed Street	10
	Sturgis Street, 38-end even, 35-end odd	14
	Thompson Street	6
	Water Street	27
	Woburn Parkway	9
	Wolcott Road	12
	Valley Road	23
17	Arlington Road, 83 to end	19
	Barton Lane	
	Border Street	12
	Buckman Court	
	Buckman Street	54
	Cove Street	
	Cranes Court	2
	Cranes Lane	
	Cross Street	3
	Fays Lane	
	Lake Avenue	66
	Lake Circle	
	Lake Terrace	
	Lydon Court	5
	Lynden Court	
	Main Street, 2 to 94 even, 1 to 107 odd	9
	Maria Court	5
	Pickering Street	11
	Stanley Terrace	6
	Stoddard Street	19
	Vining Court	10
	Wiley Street	10
18	Arlington Road, 2 t 38 even, 1 to 35 odd	114
	Bennett Street	23
	Caulfield Road, 15 to end	6
	Church Avenue, 11 to end	8

Node #	Addresses	# of Residences
	Converse Place	
	Court Street	29
	Ellis Street, 38 to end	9
	Foster Street	11
	Grove Street	11
	Harrison Avenue, 15 to 49	12
	Hillcrest Road	2
	Morse Street	
	Munroe Street	17
	North Warren Street, 1 to 60	36
	North Warren Street Ext.	
	Pleasant Street, 44 to 97	41
	Wade Place	48
	Warren Avenue, 2-38 even, 1-29 odd	27
19	Ash Street	12
	Brooks Street	4
	Buck Court	
	Buck Street	12
	Conn Street	44
	Conn Court	
	Dows Lane	
	Dow's Lane	8
	Fowle Street, 2-62 even, 1-21 odd	25
	Hudson Place	
	Hudson Street	32
	Innitou Road	13
	John Street	15
	Lakeview Avenue	
	Lakeview Terrace	20
	Lawrence Street	24
	Main Street, 96-200 even, 107A-201 odd	10
	Pierce Street	3
	Porter Street	51
	Richardson Street	41
	Richardson Street Ext.	
	Richmond Park	14
	Sturgis Street, 2-36 even, 1-33 odd	37
	Veteran Road	11
	Warren Avenue, 40-end even, 31-end odd	4
	Warren Road	4

Node #	Addresses	# of Residences
20	Edgehill Road	20
	Green Street, 1 to 17	4
	Highland Street, 2-14 even, 1-19 odd	18
	Main Street, 202 to 280	59
	Miller Place	
	Mt. Pleasant Street, 1 to 10	13
	Myrtle Street	10
	Prospect Street, 30 to end	41
	Summer Street	10
21	Buel Place	
	Caulfield Road, 1 to 14	6
	Church Avenue, 1 to 10	5
	Common Street, 1 to 6	
	Everett Street, 31 to end	7
	Gallagher Avenue	
	High Street, 1 to 40	6
	Main Street, 281 to 375	9
	Montvale Avenue, 2-50 even, 1-31 odd	4
	Prospect Avenue	8
	Prospect Street, 1 to 29	16
	Walnut Street, 21 to end	9
22	Abbott Street	
	Common Street, 7 to end	
	Everett Street, 1 to 30	12
	Federal Street	11
	Harrison Avenue, 1 to 14	3
	Main Street, 376 to 438	1
	Park Street, 1 to 23	
	Pleasant Street, 1 to 43	
	Walnut Street, 1 to 20	9
	Winn Street, 1 to 79	38
23	Campbell Street, 1 to 39	16
	Center Street	34
	Centre Street	
	Ellis Court	11
	Franklin Street	37
	Harlow Court	7
	Hovey Street	13
	Hubbard Place	
	Manns Court	10

Node #	Addresses	# of Residences
	Mann's Court	
	Main Street, 439 to 524	7
	Park Street, 24 to end	18
	Salem Street, 1 to 75	58
	Spring Street	8
	Union Street, 1 to 31	21
	Wade Avenue, 1 to 12	48
	Winn Park	37
24	Bedford Road, 1 to 33	
	Carter Place	1
	Charles Street	15
	Chesnut Street	
	Chestnut Street	49
	Church Court	4
	Church Street	24
	Colonial Road	23
	Cummings Avenue	
	David Circle	6
	Davis Street	37
	Flagg Street	17
	Frances Street	29
	Francis Street	
	Hillside Avenue	
	James Street	20
	Johnson Street	7
	Kilby Drive	4
	Kilby Street	115
	Lantern Circle	3
	Linden Circle	3
	Linden Street	11
	Linden Street Ext.	
	Lisa Drive	2
	Main Street, 526-616 even, 525-607 odd	46
	Manning Street	12
	Middlesex Street	9
	Mishawum Road, 2-10 even, 1-13 odd	9
	North Warren Street, 61 to end	72
	Plympton Street	23
	Scott Street	28
	Thistle Road, 1-5	5

Node #	Addresses	# of Residences
	Village Street	
	Winn Court	2
	Winn Street, 80 to end	78
	Wright Street	25
25	Blake Street	2
	Blake Terrace	6
	Boys Club Lane	
	Clinton Street, 1 to 15	10
	Main Street, 618 to 670 even, 609 to 671 odd	28
	Page Place	10
	Place Lane	4
26	Anderson Way	
	Brae Circle	26
	Brentwood Road, 1 to 26	23
	Brown Place	11
	Colony Road	6
	Coolidge Road	4
	Curtis Road	10
	Dickson Road	7
	Eaton Avenue, 12-30 even, 11-43 odd	20
	Eaton Lane	
	Ellen Road	15
	Elmwood Place	
	Elmwood Terrace	2
	Frances Road	29
	Frederick Circle	13
	Frederick Drive	
	Hamilton Road	28
	Hart Place	24
	Hart Street	41
	Intervale Street	11
	Jericho Road	5
	Kimball Road	13
	Lowell Street	58
	Main Street, 672 to 732	30
	Marion Avenue	14
	Meadowbrook Lane	
	Meadow Lane	
	Millyan Road	9
	Murray Road	5

Node #	Addresses	# of Residences
	Murray Road Ext.	
	Newbury Street	14
	Park Drive	38
	Park Drive Ext.	5
	Pilgrim Road	16
	Sendick Road	13
	Scheila Avenue	10
	Wilcox Circle	
	Wyman Street	51
30	Abbott Court	3
	Allen Street	11
	Arlington Street	27
	Belmont Street	13
	Blueberry Hilll Road, 1 to 38	43
	Blossom Street	4
	Bradford Road	16
	Bryant Street	13
	Carter Street	20
	Clark Street	5
	Cliffside Terrace	2
	Crest Avenue	
	Eastern Avenue, 51 to end	56
	Fowle Street, 64-end even, 23-end odd	18
	Fulton Street	20
	Garfield Avenue, 24-end even, 27-end odd	60
	Glenwood Street	13
	Golden Terrace	2
	Green Street, 18-104 even, 19-91 odd	49
	Highland Avenue	5
	Highland Street, 16-end even, 21-end odd	27
	Jefferson Court	6
	Leonard Street	32
	Madison Street	13
	Manning Court	
	McCabe Court	3
	Medford street	
	Mount Pleasant Court	
	Mount Pleasant Street, 11 to end	60
	Oxford Place	4
	Playstead Avenue	7

Node #	Addresses	# of Residences
	Skyview Lane	8
	Skyview Road	6
	Sonar Drive	
	Sonrel Street	18
	South Street	13
	Spring Court	127
	Spring Court Ext.	
	Spring Court Terrace	
	Spring Garden Terrace	
	Stoneham Street	
31	Auburn Street	49
	Campbell Street, 40 to end	132
	Fairmount Street	26
	First Street	7
	Garfield Avenue, 2-32 even, 1-25 odd	18
	Greenwood Avenue	10
	Hanson Court	5
	High Street, 41 to end	29
	Jefferson Avenue	7
	Montvale Avenue, 52-88 even, 33-87 odd	79
	Second Street	3
	Union Street, 32 to end	21
	Wade Avenue, 13 to end	48
32	Boline Place	16
	Bow Street, 1 to 32	15
	Cook Terrace	
	Eastern Avenue, 1 to 50	30
	Ferguson Place	5
	Gardner Avenue	8
	Holden Place	8
	Ingalls Street	11
	Liberty Avenue	48
	Montvale avenue, 89 to 159	54
	Montvale Lane	8
	Oakwood Lane	3
	Sherman Place	35
	Sherman Place Court	
	Sherman Terrace	
	Sullivan Place	4
	Sullivan Street	

Node #	Addresses	# of Residences
	Vernon Street, 1 to 33	31
33	Deb Road	9
	Harvard Street	16
	Laurel Street	4
	Montvale Avenue, 160 to 210	24
	Nashua Street, 88 to end	14
	Packard Street	2
	Theresa Road	6
	Wod Street, 43 to end	15
34	Blueberry Hill Road, 39 to end	
	Connors Drive	
	Draper Street	1
	Eagle Road	9
	Fieldstone Drive	16
	Fox Road	
	Frank Street	13
	Frank Street Court	
	Green Street, 106-end even, 93-end odd	14
	Hawk Road	4
	Henry Avenue	13
	Holton Street	11
	James Terrace	18
	Micro Drive	
	Moantvale Avenue, 211 to 263	12
	Nashua Street, 1 to 87	47
	Paul Avenue	5
	Pigeon Road	
	Tremont Street	30
	Vernon Street, 34 to end	17
	Williams Avenue	22
35	Asbury Avenue	12
	Central Street, 22 to 76	17
	Erie Street, 1 to 9	5
	Grape Street, 1 to 16	6
	Orange Street, 29 to end	23
	Montvale Avenue, 264 to 285	6
	Utica Street, 12 to end	4
36	A Street	
	Albany Street	14
	Central Court	

Node #	Addresses	# of Residences
	Erie Street, 10 to end	7
	Fremont Street	6
	Grape Street, 17 to end	14
	Hawthorne Street, 1 to 11	4
	Henshaw Street	1
	Hill Street	
	Mack Road	
	Maple Street	
	Merrill Street	
	Montvale Avenue, 286 to end	9
	Sherman Street	
	Utica Street, 1 to 11	6
	Washington Street, 22 to 124	39
38	C Street	
	Central Street, 77 to end	10
	D Street	
	Middlesex Avenue	
	Ran Drive	
	Washington Avenue	1
	Washington Street, 1 to 21	7
39	Albert Drive	60
	Carmen Terrace	16
	Carter Road	4
	Central Street, 1 to 21	15
	Felton Street	22
	Floyd Street	11
	Gregg Street	19
	Hawthorne Street, 12 to end	11
	Lakeview Avenue	
	Lawson Street	12
	Mill Street	213
	Mill Terrace	19
	Munroe Avenue	14
	Montvale Road, 66 to end	18
	My Street	
	Nason Terrace	
	Orange Street, 1 to 28	18
	Perry Street	6
	Pine Street, 67 to end	32
	Radcliffe Way	3

Node #	Addresses	# of Residences
	Radclyffe Way	
	Salem Street, 378 to end	10
	Unicorn Drive	
	Washington Circle	20
	Washington Street, 125 to 272	30
	Washington Terrace	6
40	Alpena Avenue	7
	Beach Street, 54 to end	16
	Bow Street, 33 to end	15
	Buttaro Road	29
	Continental Court	72
	Creston Avenue	72
	Dearborn Terrace	3
	Field Terrace	4
	Hilltop Circle	7
	Hilltop Parkway	17
	Hilltop Terrace	16
	Hyde Avenue	2
	Kathleen Drive	
	Laura Road	
	Loker Lane	
	Maple Avenue, 1 to 30	17
	Memorial Avenue	
	Parkview Road	12
	Roger Avenue	
	Rogers Avenue	5
	Salem Street, 76 to 173	48
	Sedgewick Park	9
	Sedgewick Park Ext.	
	Walnut Court	9
	Westview Terrace	11
41	Albert Street	7
	Hancock Street	3
	Hinston Road, 1 to 15	11
	Joshua Street	
	Lillian Street, 2 to 32 even, 1 to 19 odd	21
	Maple Avenue, 31 to end	12
	Salem Street, 174 to 235	23
	Sunset Avenue	5
	Wildwood Avenue, 1 to 275	

Node #	Addresses	# of Residences
	Winstead Avenue	17
	Wood Street, 1 to 42	13
42	Bird Street	11
	Chase Street	9
	Crescent Avenue	3
	Dale Street	11
	Elm Avenue	19
	Lincoln Road	9
	Montvale Road, 1 to 65	35
	Pine Street, 1 to 66	19
	Riley Road	
	Salem Street, 236 to 280	6
	Walnut Hill Park	
	Walnut Hill Street	
44	Aberjona Drive	
	Carlena Terrace	11
	Cedar Drive	
	Cedar Street	5
	Forbes Road	
	Forbes Street	
	George Avenue	13
	Lynn Street	5
	Marilyn Court	7
	Pento Road	
	Rifle Range Road	2
	Robert Avenue	14
	Salem Avenue	12
	Salem Street, 281 to 377	24
	Schneider Court	
	Spartan Circle	
	Stephanie Cr.	12
	Washington Street, 273 to 368	18
46	Anthony Drive	6
	Beach Street, 1 to 53	29
	Beach Terrace	8
	Cleveland Avenue	29
	Clinton Street, 16 to end	12
	Kendall Street	3
	KnollWood Avenue	7
	Maywood Lane	

Node #	Addresses	# of Residences
	Maywood Terrace	21
	Middle Street, 1 to 9	8
	Mishawum Road, 12 to 52 even, 15 to 51 odd	34
47	Dodge Road	1
	Dorothy Drive	3
	Eaton Avenue, 32-end even, 45-end odd	5
	Fairview Road	14
	Fairview Terrace	8
	Fryburg Road	6
	Middle Street, 0 to 63	12
	Mishawum Road, 54-74 even, 53-77 odd	23
48	Brentwood Road, 27 to end	14
	Carpenter Court	
	Cranston Cr.	7
	Edith Avenue	7
	Elaine Road	5
	Emeline Street	13
	Evangeline Lane	8
	Forest Park Road, 1 to 35	30
	Forest Park Cr.	4
	Hinston Road, 16 to end	15
	Lillian Street, 24-end even, 19A-end odd	11
	Majority Lane	
	Mishawum Road, 76-130 even, 79-129 odd	18
	Middle Street, 64 to end	26
	Overlook Avenue	3
	Phillips Street	12
	Red Leaf Lane	1
	Susan Terrace	8
49	Atwood Avenue	1
	Hall Street	3
	Highet Avenue	21
	Mishawum Road, 131 to 191	23
	Olympia Avenue, 83 to end	1
	Pine Grove Avenue	5
	Rumford Park Avenue, 18 to end	17
	University Street	1
50	Arrow Drive	
	Olympia Avenue, 61 to 82	
	State Street	

Node #	Addresses	# of Residences
	Wheeling Avenue	
	Wildwood Avenue, 276 to end	
51	Dewey Avenue	18
	Hobson Avenue	2
	Marietta Street	6
	Normac road	
	Olympia Avenue, 1 to 60	7
	Oregon Avenue	2
	Wainwright Avenue	2
	Washington Street, 369 to 443	7
52	Alfred Street, 24-end even, 27-end odd	16
	Barbara Circle	19
	Boyd Road	24
	Cronin Way	
	Forest Glen Circle	7
	Forest Glen Road	8
	Forest Park Road, 36 to 95	14
	Rumford Park Avenue, 1 to 17	11
	Thomas Street	12
53	Emerson Road	3
	Forest Park Road, 96 to end	8
	Hope Lane	8
	Karen Road	13
	Lucia Terrace	
	New Boston Street, 1 to 133	
	School Street, 80 to 203	38
	Woodside Terrace	22
54	Alice Road	5
	Allan Street	2
	Bronislaw Street	12
	Jan Road	
	Jan Street	12
	Old Mishawum Road	3
	School Street, 204 to end	15
	Mishawum Road, 192-230 even, 195-275 odd	4
55	Adele Road	
	Gill Street	
	Everberg Road	
	Industrial Pkwy., 16-end even, 31-end odd	
	Industrial Road, 16-end even, 31-end odd	

Node #	Addresses	# of Residences
	New Boston Street, 134 to 181	
	Roessler Road	
	Sixth Road	
	Torrence Road	
56	Industrial Pkwy., 2-14 even, 1-29 odd	
	Industrial Road, 2-14 even, 1-29 odd	
	Linscott Road	
	Mishawum Road, 232-278 even, 277-279 odd	
	Rath Road	
	Ryan Road	
57	Commerce Way, 1 to 36	
	Elmwood Street	10
	Forest Avenue	
	Forest Street	1
	Garden Terrace	12
	Mishawum Road, 280 to end	7
58	Dragon Court, 1 to 19	6
	Dragon Court Circle	6
	Richard Cr.	49
	Washington Street, 444 to end	9
59	Atlantic Avenue	
AKA 57	Cabot Road	
	Commerce Way, 37 to end	
	Commonwealth Avenue	
	Constitution Avenue’	
	Puritan Ave East	
60	Dragon Court, 20 to end	8
AKA 58	Florence Terrace	2
	North Dragon Court	
61	Dundee Drive	
	East Dexter Avenue, 101 to end	
	Fifth Road	
	First Road	1
	Fourth Road	
	Merrimac Street, 76A to end	17
	New Boston Street, 182 to end	
	North Maple Street	
	Oakland Street	
	Palmer Street	
	Presidential Drive	

Node #	Addresses	# of Residences
	Rumford Avenue	
	Third Road	9
	Torrice Drive	
	Undercover Way	
62	Alfred Place	
	Alfred Street, 2-22 even, 1-25 odd	6
	Alfred Street Ext.	
	Alfred Terrace	6
	Baldwin Green	2
	Elm Street, 1 to 29	9
	Fisher Terrace	25
	Fletcher Road, 28 to end	26
	Giacalone Lane	
	Giacalone Road	
	Harold Avenue	9
	Main Street, 733 to 869	3
	Middlesex Canal Park	
	Rear Alfred Street	
	True Place	
	Van Norden Road, 19 to end	15
63	Elm Street, 30-72 even, 31-61 odd	24
	Newbridge Avenue	11
	Patricia Cr	7
	Perry Place	5
	Tidd Avenue	6
	Traverse Street	6
	Ward Street	22
	West Street	30
64	Elm Street, 74-end even, 63-end odd	6
	Edwards Road	24
	Keith Circle	16
	Knight Avenue	
	Main Street, 870 to 901	3
	School Street, 1 to 13	11
	Traverse Street	
65	App Court	6
	Dexter Avenue, 1 to 13	12
	Donna Road	10
	Donna Road Ext.	
	East Nichols Street	14

Node #	Addresses	# of Residences
	Lord Terrace	2
	Main Street, 902-972 even, 903-949 odd	30
	Minot Street	7
	Nichols Street	19
	O'Neil Road	2
	Pettiglio Terrace	2
	Rear Dexter Avenue	
	Wilson Street	
	Wyman Place	
66	Baldwin Avenue	2
	Banks Street	3
	Chester Avenue	21
	Cottage Street	3
	Cutting Avenue	1
	Danford Avenue	4
	Daniel Drive	
	East Dexter Avenue, 14 to 100	
	Dartmough Street	12
	Eighth Road	1
	Fletcher Road, 1 to 27	19
	Foster Avenue	7
	Hensel Avenue	
	Jones Avenue	8
	Longwood Avenue	8
	Merrimac Street, 1 to 76	22
	Michael Circle	34
	Mostika Road	4
	Poplar Street	7
	Prescott Street	
	School Street, 14 to 79	48
	Tyler Street	
	Van Norden Road, 1 to 18	10
	Williams Court	5
67	Gatta Circle	13
	Poole Street, 2-34 even, 1-39 odd	30
	Nichols Street Ext.	54
	Webster Avenue	60
	Webster Avenue Ext.	3
	Webster Court	
	Webster Street, 1 to 19	1

Node #	Addresses	# of Residences
68	Bartlett Drive	26
	Dickie Road	9
	Florence Road	
	Kendal Drive	
	Kendall Drive	17
	Kimball Court	1
	Pearl Street	292
	Spring Garden Terrace	4
	Sunnyside Road	
	Sylvan Road	2
	Webster Street, 20 to end	11
	Westgate Drive	
69	Briarwood Road	16
	Cedar Road	10
	Mountain Street, 45 to end	19
	Poole Street, 36-end even, 41-end odd	9
	Robinlea Circle	12
	Winter Road	49
	Winter Street	11
	Williams Lane	6
70	Ashburon Avenue	20
	Breed Avenue	
	Delaware Avenue	2
	Ford Terrace	2
	Indiana Avenue	2
	Kearsage Avenue	6
	Kentucky Avenue	4
	Lamoil Street	6
	Lancaster Street	
	Lee Street	
	Lenox Avenue	
	Leslie Avenue	
	Main Street, 974-end even, 951 to end odd	145
	Massachusetts Avenue	2
	Marian Street	2
	Milan Avenue	25
	Montgomery Avenue	
	Mountain Street, 1 to 44	17
	Naples Avenue	10
	North Maple Street	16

Node #	Addresses	# of Residences
	Park Avenue	
	Pennsylvania Avenue	
	Richmond Avenue	11
	Summit Avenue	
	Tennessee Avenue	1
	Tennessee Street	
	Thurman Street	
	Townsend Street	
	Virginia Avenue	2
	Wachusett Avenue	
	Washington Avenue	8
	Wheeling Street	3

TABLE 6
INPUT VARIABLES FOR THE COMPUTER MODELS

Variable	Symbol	Typical value	Data error level
Pipe Length	L	4200 ft.	50 ft.
Pipe diameter	D	12 in.	0.1 in.
Pipe connections	none	Node number	none
Pipe roughness	C	80	40
Node water demand	Q_d	181 gal./min.	60 gal./min.
Node elevation	Z	161 ft.	1 ft.
Reservoir level	Z	312 ft.	1 ft.
Pump flow rate	Q_p	600 gal./min.	6 gal./min.
Pump total head	H_p	264 ft.	3 ft.
Well water level	Z	40 ft.	2 ft.
Check valve sites	none	Pipe number	None
Pollutant concentration	P	0.58 ppm	0.01 ppm