Evaluation of Contaminant Sources & Transport in the Wachusett Reservoir Watershed

prepared by

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for

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Outline

Signed,

William W. Walker, Jr.

July 27, 1999
Date

1. Qualifications

I have 28 years experience in Environmental Engineering, 21 of which as an independent consultant to federal & state agencies, municipal water utilities, developers, and private industries (Appendix E). I have Bachelors and Masters degrees in Chemical Engineering from MIT and a Ph.D. in Environmental Engineering from Harvard. My expertise is in evaluating water quality problems and developing control strategies. My projects have generally involved design of water-quality monitoring programs, statistical analysis of monitoring data, and mathematical modeling of contaminant sources, transport, and fate in streams, lakes, and reservoirs. For various state and federal agencies, I have developed several computer programs that are widely used by others in my field, including the P8 Urban Catchment Model for simulating pollutant transport in watersheds and designing pollution control measures. This model has been used by MDC/MWRA consultants in studies of the Wachusett watershed.

In 1970, I received an award from the American Institute of Chemists for an outstanding student in Chemical Engineering. In 1988, I received an award from the North American Lake Management Society for outstanding research in lake restoration, protection, and management. In 1991, I received an award from the Governor of Rhode Island for outstanding projects that promote environmentally sensitive land development and protect water quality. In 1994, I received a certificate of appreciation from the U.S. Department of Justice in recognition of outstanding service and dedication to the cause of Everglades ecosystem preservation and restoration. My municipal water-utility clients have included New Haven, Baltimore, New York, Oakland, Los Angeles, Seattle, St. Paul, and Cambridge. My current clients include the U.S. Department of Justice, U.S. Department of the Interior, St. Paul Water Utility, South Florida Water Management District, Onondaga County (New York), Michigan Department of Natural Resources, and the University of Wisconsin.

2. Summary of Opinions

The Department of Justice has asked me to develop opinions on risks to the MWRA water supply associated with contaminant generation and transport in the Wachusett Reservoir watershed and on the potential effectiveness of watershed management in controlling those risks. Terms of my contract with the Department of Justice are described in Appendix D. In developing my opinions, I have:

- reviewed numerous reports & documents specific to watershed and to this case
- inspected the watershed
- analyzed GIS (Geographic Information System) data provided by the MDC
- analyzed water quality & hydrologic data collected by the MDC, MWRA, etc.
- reviewed recent literature on coliform/pathogen dynamics & control strategies

To support its watershed protection and management efforts, the MDC has compiled an impressive database on land use, hydrographic, and geologic features of the watershed. Land use and population data indicate that the watershed contains potential sources of pathogens and other water-supply contaminants associated with natural background conditions, agricultural land uses, and urban land uses. Transport of contaminant loads from source areas to Wachusett Reservoir is fostered by steep terrain and shallow soils in some areas and by the proximity of existing developed areas to streams and to the Reservoir itself.   Soils in the area are poorly suited for septic systems, which currently provide the only form of wastewater treatment for the more than 30,000 people residing in the watershed. A portion of the land designated by the MDC/MWRA as "Preserved and Protected Open Space" has already been developed and continues to pose contamination risks.

The presence of fecal coliforms in a water sample indicates risk of contamination by pathogenic organisms of fecal origin. Fecal coliform counts at watershed monitoring stations are strongly correlated with upstream agricultural and urban land uses during dry and wet weather. Substantially higher counts observed during and following storm events indicate that both stormwater runoff and failing septic systems may contribute contaminants of fecal origin to streams and to the Reservoir. The apparent importance of stormwater runoff and agricultural land uses indicate that construction of sewers in a portion of watershed will address only portion of the fecal contamination problem.

As sources of drinking water, tributaries of Wachusett Reservoir have been designated by the Commonwealth as Class A waters. I estimate that average annual inflow fecal coliform concentration to the Reservoir from the watershed exceeds 80 cfu/100ml, or 4 times the Massachusetts Class A standard of 20 cfu/100ml. Concentrations are nearly 4 times higher in the more developed watersheds and 10 or more times higher during some storm events. The average fecal coliform concentration exceeds the Class A standard in 12 out of 12 monitored streams discharging directly into the Reservoir and 9 out of 13 monitored streams located in upper regions of the watershed. This indicates that sources of pathogen indicators are widespread and will be difficult to specifically identify and control.

In attempting (unsuccessfully) to meet EPA's filtration avoidance criteria, the MWRA has been relying upon the dilution of contaminated watershed runoff by rainfall and Quabbin diversions and upon natural "treatment" processes occurring within the Reservoir. Even if rainfall and Quabbin diversions are assumed to be contaminant- free (not necessarily the case), dilution reduces average inflow concentrations by a factor of about 2.3, much less during periods runoff when diversions from Quabbin are stopped. Potential rates of contaminant transport through the Reservoir vary significantly with contaminant type, water temperature, hydrodynamics, and other environmental factors. Available data indicate that the Reservoir is unlikely to provide significant removals of pathogenic protozoans because of their long survival times and low settling rates.

Fecal coliform (pathogen indicator) data collected at the Cosgrove Intake to the MWRA supply demonstrate that dilution and natural reservoir processes cannot be relied upon to transform contaminated watershed runoff into drinking water that does not require filtration. Fecal coliform levels at the Intake exceeded EPA's filtration avoidance criteria in 1990, 1991, 1992, 1993 and again in 1999 from January at least through mid May. I disagree with the notion that gulls are the only source of fecal coliforms reaching the MWRA Intake. Fecal coliform measurements at the Intake are positively correlated with antecedent precipitation. This suggests that storm-driven pulses of fecal coliforms from the watershed reach the Intake, albeit at lower concentrations because of dilution, dispersion, and die-off mechanisms. These signals are clearly present across different seasons and year, despite "noise" in the data resulting from inherent variability of bacteria populations and seasonal impact of gulls. Given that some pathogens (viruses, protozoans, including Cryptosporidium) are known to be more persistent in the environment (i.e. live longer) than fecal coliforms, pathogens entering the Reservoir from the watershed are more likely than fecal coliforms to be transported to the Intake.

Watershed protection and management efforts undertaken by the MDC are consistent with the state-of-the-art and should continue, regardless of whether a water filtration plant is constructed. These measures are potentially effective for reducing the extent and impacts of future development, but likely to be less effective in controlling contaminant loads from existing urban and agricultural areas. Detention ponds and similar treatment devices being considered for implementation in existing and future developed areas may be partially effective in removing some types of contaminants (suspended solids, nutrients, heavy metals), but are not expected to provide significant removals of Cryptosporidium, Giardia, other persistent pathogens, or other contaminants associated with fine particles. Given the difficulties associated with identifying specific contaminant sources, limitations of the control measures, and uncertainties in forecasting their performance, there is currently no reliable quantitative basis for predicting the net benefits of all control measures being implemented to reduce existing contaminant loads to the Reservoir. These benefits will be at least partially offset by impacts of ongoing development.

The USEPA has established a Maximum Contaminant Level Goal (MCLG) of 0 organisms/100 liters for Cryptosporidium. This value reflects well-documented risks to public health associated with this organism. Given the MCLG of 0, the difficulties and uncertainties associated with controlling contaminant sources in the watershed, and the ineffectiveness of the Reservoir as a pathogen barrier, the MWRA should be required to apply the best available water treatment technology. Providing safe drinking water requires multiple barriers: watershed protection, watershed management, filtration, and disinfection.

3.0 Conceptual Model

Contamination of source waters by natural or anthropogenic sources can have a variety of direct and indirect impacts on the quality of water supplied to consumers. Direct effects result when pathogens or toxic materials originating in the watershed break through the treatment system and reach consumer taps. Indirect effects result when other types of contaminants, not necessarily toxic, cause degradation of reservoir water quality which, in turn, hinders the performance of water treatment processes and increases the risk of pathogen or other toxicant breakthrough. One example of a secondary impact is nutrient enrichment, which increases the organic and particulate content of the source water and sometimes interferes with filtration and disinfection processes. To a limited extent, contaminant sources can be controlled by watershed protection (generally seeking to avoid creation of new contaminant sources) and watershed management (seeking to reduce existing sources). Like water treatment systems, watershed protection and management measures have limited and varying performance. Hence, the concept of "multiple barriers" is important to provide safe drinking water.

My conceptual model of the watershed is generally similar to that embodied in the Watershed Management Plan (MDC,1998) and numerous reports produced by MDC/MWRA consultants (Rizzo Assoc., 1991; Comprehensive Environmental 1997; ENSR,1998; CDM, 1999). The basic concepts of Sources, Transport, and Fate provide a basis for discussing Wachusett watershed features and management measures in subsequent sections.

A diverse watershed such as Wachusett is likely to contain a variety of natural and anthropogenic contaminant sources (Reilly, 1999). Natural sources of pathogenic protozoans of sources can be important, particularly in the case of pathogenic protozoans that have been commonly found in undeveloped watersheds (LeChevallier et al, 1991; Rose, 1997). Contaminant sources associated with urban or agricultural land uses include people, pets, livestock, automobiles, fertilizers, pesticides, industrial chemicals, land erosion, etc. (Reilly, 1999; USEPA, 1993). Levels of fecal coliform bacteria and risk of water-supply contamination with pathogens generally increases with agricultural or urban land use (Rose, 1997, 1999; Clancy, 1999; CWP, 1999). Given the spatial diversity of watersheds and wide array of potential contaminant sources, identifying the specific origins of contaminants measured at the mouth of a watershed can be very difficult. This, in turn, makes it difficult to control them, even if regulatory authority, technology, and financial resources exist.

Contaminants are transported from source areas to the mouth of a watershed in surface runoff and groundwater flow that eventually enters streams. Two watersheds with the same land uses may have very different net impacts on reservoir water quality, depending upon how the land uses are spatially distributed, extent of constructed drainage systems, and inherent terrain features (geology, topography). Some contaminants (including pathogens) are partially removed when rainfall infiltrates and moves through the soil before reaching a storm sewer, drainage ditch, stream, or other surface water body. The potential transport of contaminants in surface runoff is lowest in watersheds with flat terrain, sandy/well-drained soils, limited impervious cover, and low drainage densities (miles of stream channel per square mile of watershed). Transport is highest in watersheds with steep terrain, shallow/impermeable soils, impervious surfaces, and high drainage densities. While providing drainage and flood protection for urban and agricultural land uses, construction of storm sewers and channelization of streams promote contaminant transport. Impacts of effluents from onsite wastewater disposal (septic) systems are controlled by age, unit area loads, land slope, soil characteristics, and proximity to drainage canals and surface water bodies.

The distance between developed areas and the drainage network (storm sewers, streams, or the reservoir itself) is an important factor determining potential transport of contaminants originating in surface runoff and septic systems. This "buffer" concept is fundamental to the Watershed Protection Act (Commonwealth, 1992) and to MDC's prioritization of regions for watershed protection (land purchase) and management (MDC, 1998. CDM, 1999). Risk of contaminant transport to a stream/reservoir is highest in developed areas intersecting or within buffer zones.

The fate, or ultimate destination, of a contaminant discharged from a source in water-supply watershed can include: (1) immobilization in soils or stream sediments; (2) die-off or decay due to natural processes occurring on the land surface, soils, streams, or reservoirs; (3) removal in detention ponds or other treatment devices that might be constructed under a watershed management plan (3) removal in water treatment facilities; or (4) public consumption. The fate of a specific contaminant depends upon its physical, chemical, and biological characteristics, upon the watershed and reservoir features that control contaminant transport, and upon the effectiveness of watershed management and water treatment facilities as protective barriers.

4.0 Analysis of Watershed Features

4.1 Introduction

Geographic Information System (GIS) data describe the spatial distribution of watershed features that reflect potential sources and transport of contaminants. The extensive GIS database compiled by the MDC provides an important foundation for its watershed management and protection efforts. While MDC's Watershed Management Plan (1998) and Stormwater Management Plan (CDM, 1999) summarize this information in various ways, I have analyzed it to obtain independent perspectives on the following:

- <u>Potential Contaminant Sources</u>, based upon distributions of existing land use, transportation corridors, and population density;

- Potential Contaminant Transport, based upon geology, soil types, and proximity of potential source areas to streams and reservoirs (water-supply protection zones);

- Status of Protected Areas, based upon inventories of existing land uses in areas the have been designated by the MDC as "protected" according to various criteria.

Maps and tables produced in this analysis are contained in Appendix A.

The GIS database on the Wachusett watershed (MassGIS, 1997,1999) contains a series of "coverages", each of which describes the spatial distribution of a specific watershed feature. The database includes coverages describing the drainage network (subwatersheds, streams, lakes, reservoirs), topography, geology, land use, buffer zones regulated under the Water Supply Protection Act (Commonwealth, 1992), and parcel zoning/ownership. Additional insights can be gained by overlaying two or more coverages to characterize, for example, the distribution of land uses within each subwatershed or within each WSPA buffer zone.

4.2 Basic Features

A drainage map of the Wachusett Reservoir and Watershed is shown in Figure A-1. The total watershed area is 117 mi^2, including the Reservoir surface (6.0 mi^2) and approximately 2.9 mi^2 of upstream lakes and impoundments. The MDC has delineated the area into 41 subwatersheds (Figure A-2), each of which is further classified into 5 "Sanitary Districts" or major drainage basins (Worcester, Quinapoxet, Stillwater, Thomas Basin, Reservoir). Because of diversions for the City of Worcester water supply, the Worcester District contributes relatively little flow to Wachusett Reservoir, except during periods of high runoff (CDM, 1999). Deducting the Worcester district and surface area of Wachusett Reservoir, the contributing watershed is estimated at 82.9 mi^2.

According to the MDC (1998, Table 2-6), the local watershed contributes approximately 44% of the total inflow to the Reservoir. The remainder is attributed to direct precipitation (5%) and diversions from Quabbin Reservoir (51%), which enter the system near the mouth of the Quinapoxet River (Figure A-2). The percentage contribution from the watershed is greater during periods of high runoff, when concentrations and loads of fecal coliforms and other contaminants in watershed streams also tend to increase (CDM, 1999). Primary outflows from the Reservoir include the Cosgrove Aqueduct (92%), spillage to the Nashua River downstream of the Reservoir (5%), and evaporation (2%).

Based upon the water balance, dilution by direct rainfall and Quabbin diversions would be expected to reduce the average concentrations of any contaminants in watershed inflows by a factor of about 2.3. The actual reduction would be somewhat less because the calculation assumes that rainfall and Quabbin diversions are contaminant free. There would be less dilution during periods of high runoff, when diversions from Quabbin are stopped.

4.3 Contaminant Sources

While the Wachusett Reservoir watershed contributes 44% of the MWRA water supply volume, it contributes a higher proportion of the total contaminant load to the Reservoir and to the MWRA intake because the Quabbin/Ware watersheds are less developed (MDC, 1998). Although natural sources of fecal coliforms, pathogens, and other contaminants exist, loads would be expected to increase with urban or agricultural development (Section 3).

The following maps illustrate features related to land development and potential contaminant sources:

Figure A-3	Land Uses
Figure A-4	Roads & Railroads
Figure A-5	Population Density

Figure A-6 Worcester County Population Density

Using aerial photographs taken in 1992-1993, the MDC has classified existing land uses into 52 classes (Table A-1). To simplify the maps and provide general perspectives on the extent of development, I have grouped the classes into undeveloped, agricultural, and urban categories, as shown in Figure A-3. Land use data are summarized by class and category in Table A-1 and by region (subwatershed, sanitary district, total watershed, contributing watershed) in Table A-2. These tables and all quoted percentages below exclude the Wachusett Reservoir surface.

Risk of water supply contamination is indicated by the fact the total watershed contains approximately 5,394 acres of agricultural land and 8,728 acres of urban land (Table A-2, Figure A-3). Corresponding values for the contributing watershed are 3,683 acres and 7,536 acres, respectively. Percentage land use distributions are 8% agricultural, 12% urban, and 80% undeveloped for the entire watershed and 7%, 14%, and 79% for the contributing watershed, respectively. These results are comparable to those reported in the Watershed Management Plan (MDC, 1998, Table 2-1, (8% agricultural, 9% residential, 0.6% commercial/industrial, and 7% Other). MDC's "Other" category may contain land uses such as transportation corridors, mining, golf courses, waste disposal, etc., that I have placed in the "urban" category, as indicated in Table A-1. Within the urban category, dominant land uses are light residential (50% of all urban uses) and medium-density residential (17%). Although they account for a relatively small percentage of the total watershed, commercial and industrial uses total 455 acres and should not be discounted as potential contaminant sources. Within the agricultural category, dominant land uses are cropland (54%) and pasture (37%). On a subwatershed basis (Table A-2, Figure A-3), agricultural percentages range from 0 to 26%, urban percentages range from 0 to 50%, and total developed (agricultural + urban) percentages range from 0 to 62%.

Roads and railways that cross the watershed (Figure A-4) contribute surface runoff to the water supply and pose risks associated with accidental or intentional chemical spillage.

The railways and major roads (I90, Route 140, Route 110) that pass relatively close to the reservoir of particular concern in this regard. In touring the watershed, I observed road sections that drain directly into the Reservoir without opportunity for overland flow or infiltration that would otherwise provide some buffering capacity or "treatment". Direct road drainage to tributaries is common throughout the watershed

The 8,728 acres of urban land in the land use database include only a portion of 2,248 acres of road surfaces that follow and/or cross streams within the watershed. I extracted the roads shown in Figure A-4 from MDC's parcel database, then intersected them with the land use coverage. Results indicate that the 2,232 acres of roads include 1,019 acres of land incorrectly classified as undeveloped in the land use database, 172 acres of agricultural land, and 1,041 acres of urban land. If road surfaces classified as undeveloped or agricultural are added to the urban category, the total urban area increases from 8,728 acres to 9,919 acres and the total agricultural area decreases from 5,394 acres to 5,222 acres.

Figure A-5 shows the approximate spatial distribution of population within the Wachusett watershed, based upon the 1990 Census (USBC,1990). The MDC (1998, Table 2-1) reports an average population density of 284 mi^2. Risks associated with pathogens and other contaminants derived directly or indirectly from human sources are indicated by the fact that the watershed contains more than 30,000 residents, essentially all of which are served by onsite wastewater disposal systems. Population density is relatively high in the Gates Brook and other smaller watersheds that drain directly in to the southwestern end of the Reservoir. Potential impacts on the water supply related to land development pressure, traffic, recreation, and other human activity in the watershed are indicated by proximity of the watershed to Worcester and other regions with high population density (Figure A-6).

4.4 Transport

Transport of contaminants from source areas to tributaries and the Reservoir is promoted by geologic features of the watershed and by the spatial distribution of developed areas. The following GIS maps illustrate factors controlling contaminant transport:

A-7 Surficial Geology
A-8 Land Slopes
A-9 WSPA Buffer Zones
A-10 Land Uses Overlayed on WSPA Buffer Zones

Consistent with impressions I received in touring the watershed, soil properties and generally hilly terrain are likely to promote contaminant transport in surface runoff and septic system effluents. Much of the watershed is classified as "glacial till and bedrock" (Figure A-7). These types of soils generally have high runoff potential, particularly in hilly terrain (Figure A-8). The performance of septic systems is likely to be relatively poor in areas with shallow soils/exposed bedrock or in areas with extensive sand and gravel deposits following stream courses (USEPA,1993). According to ENSR(1998), the particular soil classes found in the Gates Brook (most highly developed, Table A-2) watershed have "extremely rapid permeability or very slow permeability with perched groundwater table that severely limits most soils for subsurface wastewater disposal".

Contaminant transport is also facilitated by the fact that development has occurred in areas that are in close proximity to the Reservoir and tributaries. Figure A-9 shows stream and reservoir buffer zones potentially regulated under the Watershed Protection Act (Commonwealth, 1992). The "Primary" Zone (13,282 acres, excluding reservoir surface, Table A-1) includes areas within 400 feet of the Reservoir and within 200 feet of tributaries. The "Secondary" Zone (11,681 acres) includes areas between 200 and 400 feet of tributaries, as well as areas within floodplains, over some aquifers, and within bordering vegetated wetlands (MDC,1998). Under the Act, the ability to regulate existing developed areas within these buffer zones is limited (USEPA, 1999).

Figure A-10 shows land uses and roads overlayed on MDC buffer categories. Corresponding data are summarized in Table A-1. Risk of contamination is highest from 472 acres of agricultural land and 921 acres of urban land located completely within the Primary Zone. The Secondary Zone contains 789 acres of agricultural land and 1,647 acres of urban land. Risk of contamination is lower, but still significant from the remaining 4,133 acres of agricultural land and 6,160 acres of urban land in the watershed. As discussed above, these figures include only a portion of road surfaces and railway beds that follow and/or cross streams within the watershed (Figure A-4).

4.5 Status of Protected Areas

Land "protection" measures (public ownership, conservation restrictions, etc) are effective measures for limiting the extent and impacts of future development in the watershed. This is a cornerstone concept in MDC's watershed management program (MDC, 1998). Such measures are much less effective, however, for controlling impacts of pre-existing development. Once the land is cleared and/or paved, the potential for contaminant transport in surface runoff remains, regardless of ownership. Over a long time frame, some benefits may be derived from reductions in use intensities and/or categories (e.g., allowing agricultural areas to revert to forest).

Table 2 (p. ES-13) of the Watershed Protection Plan (MDC, 1998) defines "MDC and Other Protected Open Space" in the Quabbin, Ware, and Wachusett watersheds. The Table indicates that 52% of the watershed is protected, 26% by MDC (or DEM) ownership and 26% by other government ownership, Chapter 61, 61A, 61B, other conservation restrictions, etc. Corresponding areas are 18,074 acres (MDC,1998, Table 4-4) and 18,385 acres (Table 4-8), respectively, for a total of 36,459 acres.

I have attempted to reproduce MDC's estimates by extracting data from the parcel GIS coverage. This database contains detailed information on ownership, use classification, value, and open space designation for more than 14,000 individual parcels in the watershed (Figure A-11). Results (Table A-1) indicate a total of 17,955 acres in MDC or DEM ownership and 19,898 acres otherwise protected, for a total of 37,852 acres. The "otherwise protected" category includes parcels protected under Chapter 61 (Forest), 61A (Agricultural), or 61B (Recreation/Conservation) or with designated open space ownership. My total differs from MDC's estimate by 4%. These results are in reasonable agreement, considering that the MDC may have used a different version of the GIS database and/or other sources of information in deriving its estimates. The spatial distribution of protected areas is shown in Figure A-12.

Existing land uses within each protection category are shown in Figure A-13 and listed in Tables A-1. The "Preserved and Protected Open Space" cited in Table 2 (MDC, 1998) includes approximately 3,138 acres of agricultural land and 1,244 acres of urban land. These correspond to 8.3% and 3.3% of the total protected area, respectively. The agricultural category includes 1,762 acres of cropland, 1,037 acres of pasture, 195 acres of orchard, and 143 acres of nursery. The urban category includes 294 acres of light residential, 203 acres of golf course, 193 acres of powerline, 137 acres of transportation corridor, 80 acres of waste disposal, 78 acres of recreational, 63 acres of mining, 60 acres of cemetery, and 26 acres of commercial/industrial. While the some of the urban land uses have relatively low intensity, they should not be considered "Open Space" from a water quality perspective. If existing developed areas are removed from Table 2 (MDC, 1998), the percent protected decreases from 52% to 45%.

MDC (1998, p. ES-13) estimates that 69% of the watershed is either protected according to the above criteria or regulated under the Water Supply Protection Act. Figure A-14 shows the land use distribution over these areas. Protection and regulation efforts are clearly in the best long-term interest of the water supply. Given the existing development in these areas, however, they should not be discounted as potential sources of contaminants.

5.0 Analysis of Fecal Coliform Monitoring Data

5.1 Introduction

Fecal coliform measurements are widely used as indicators of fecal contamination in surface and groundwaters (APHA,1995; Boyer & Pasquarell, 1999; USEPA, 1998; CWP, 1999). The presence of fecal coliforms in a water sample is commonly taken to indicate a risk of water contamination from fecal material that may also contain pathogenic organisms, including other bacteria, viruses, and protozoans. While there is by no means a one-to-one relationship between fecal coliforms and pathogens, fecal coliform measurements are the most practical and widely used method to indicate risk of contamination and disease transmission in water supplies. Compared with direct measurements of pathogens (some of which may be as yet undiscovered), reliable fecal coliform counts are relatively easy and inexpensive to obtain. These properties enable collection of large numbers of samples necessary to obtain an adequate assessment at a given monitoring station, given the inherent variability of bacteria populations. The relevance of fecal coliform data is reflected by the extensive monitoring conducted by the MDC in the Wachusett Watershed and Reservoir over the past several years.

I have conducted extensive statistical analyses of fecal coliform data collected by the MDC in the Wachusett watershed and by the MDC and MWRA at the Cosgrove Intake to the MWRA system. I have examined spatial and temporal variations in the data and evaluated correlations with land use, precipitation, season, and year. I have focused on data collected between January 1994 and May 1999. This period reflects the status quo after implementation of gull-control measures that may have caused reductions in fecal coliform levels at the MWRA intake, compared with levels measured prior to January 1994 (MDC, 1998; MWRA & MDC, 1998). My results are documented in Appendix B and discussed below.

Coliform and supporting hydrologic data have been compiled with assistance from the USEPA. EPA has located and consolidated data from electronic and paper files provided by the MDC/MWRA. Other supporting climatologic data from the Worcester Airport have been obtained from the National Oceanographic and Atmospheric Administration via the Internet. I have combined files from these various sources and converted them into formats that are conducive to graphical and statistical analyses.

5.2 Watershed Fecal Coliform Data

The locations of watershed monitoring stations are shown in Figure A-15. The data set includes 5,417 fecal coliform measurements collected at 42 locations. Table B-1 lists station locations, periods of record, and statistical summaries[1]. Stations are referenced by subwatershed number (Figure A-2). Watershed stations were generally sampled at weekly to monthly intervals, though not all were operational for the entire 1994-1998 period.   I have classified the watershed stations into three categories:

- <u>Primary Stations</u>**.** most downstream station in each subwatershed draining directly into Wachusett Reservoir or Thomas Basin;
- <u>Secondary Stations</u>**.** most downstream station in subwatersheds further up in the drainage system; and
- <u>Tertiary Stations</u>**.** other stations located above primary or secondary stations in various subwatersheds.

My analysis focuses on 25 primary and secondary stations that most closely reflect the output from each subwatershed. Tertiary stations have been less consistently sampled and would be useful for more detailed evaluation of upstream/downstream variations within each subwatershed.

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[1] Fecal coliform concentrations were occasionally reported at "TNTC" or "Too Numerous to Count". In plotting the data (Figure B-1) and in computing means, I have assigned a numerical value of 10,000 cfu/100ml, near the upper limit of quantified values. Counts in the range of 10,000 - 20,000 cfu/100 ml were reported in several samples. In computing geometric and means, I have assigned a numerical value of 0.5 cfu/100 ml to values that were reported as 0 cfu/100 ml, or below detection. If a value was reported as less than some number, I have assigned a numerical value half that number (ie., "<50" would be assigned a numeric value of 25 cfu/100ml).

Watershed fecal coliform time counts at primary monitoring stations are plotted over time in Figure B-1. Frequencies of values exceeding 20 cfu/100 ml are mapped in Figure A-16. At primary stations (entering reservoir), fecal coliforms exceeded 20 cfu/100 ml in 46% of all samples (Table B-1).

As sources of drinking water, tributaries of Wachusett Reservoir have been designated by the Commonwealth as Class A waters. The Massachusetts Class A standard for fecal coliforms is an arithmetic mean of 20 cfu/100 ml (USEPA, 1998). The arithmetic mean of all samples is 120 cfu/100 ml at primary stations and 136 cfu/100 ml at secondary stations (Table B-1). The mean concentration exceeds the Class A standard in 12 out of 12 primary watershed stations and 9 out of 13 secondary stations. Substantial reductions in fecal coliforms would be required to bring the tributaries into compliance with the Class A standard. Sources of pathogen indicators are widespread and will be difficult to specifically identify and control.

The widespread occurrence of high fecal coliform levels at watershed outlets confirms that fecal coliform loads are transported from source areas in the watershed, down the streams, and into the Reservoir. There is a significant risk that pathogenic organisms are transported along with them. In fact, there is more than a risk, given that protozoan pathogens have been detected at tributary stations (MWRA,1998; Rose, 1999). These observations are consistent with the conceptual model discussed in Section 3 and with the land-use distribution, high transport potential, and other risk factors described in Section 4.

To support development of the MDC's Stormwater Management Plan, CDM (1999, Section 2 of Appendix) analyzed these same data and concluded that concentrations of fecal coliforms and nitrates at watershed stations were strongly correlated with upstream agricultural and urban land uses. Similar results were obtained in MDC's 1997 Stormwater Study (CDM, 1999, Appendix Table 2-6). My results (Tables B-2 & 3 and Figures B-2,3,4, & 5) also indicate a strong correlation between measured fecal coliform counts and upstream land use.

Cumulative land uses for each subwatershed extracted from the GIS database (Appendix A) are listed in Table B-2. These values are paired with monitoring data from the corresponding primary and secondary monitoring stations in Table B-3. Figure B-2 shows geometric mean fecal coliform counts at each station in dry and wet weather, paired with upstream agricultural and urban land uses. Figure B-3 shows frequencies of values exceeding the 20 cfu/100ml standard paired with land uses.

I have placed samples into dry- and wet-weather categories based upon the total precipitation in the 3 days prior to sampling. A sample is classified as "dry" if the 3-day precipitation is less than or equal to 0.2 inches and "wet" otherwise.[2]. This amount of precipitation is generally sufficient to generate surface runoff from watersheds with mixed land uses. A similar criterion was used by CDM (1999) to distinguish dry- and wet-weather samples. The importance of stormwater runoff as a source of fecal contamination is indicated by the fact that wet-weather geometric means exceeded dry-weather values at 24 out of the 25 stations (Figure B-2).

Figures B-2 and B-3 also show that fecal counts increase with upstream urban and agricultural uses. At stations with the least amount of development (Hastings Cove, Justice, Keyes) the 20 cfu/100 ml standard was exceeded in less than 10% of the dry and wet-weather samples. At stations with the greatest amount of development (W. Boylston, Scarlett, Gates), the standard was exceeded in 72-80% of the wet-weather samples and 6-67% of the dry-weather samples.

Two regression models relating fecal coliform counts to upstream land uses are shown in Figures B-4 and B-5, respectively. In the former, bacteria counts are correlated with agricultural and urban land uses separately. Model coefficients indicate that the correlation with agricultural land uses is slightly stronger than the correlation with urban

[2] To estimate precipitation that is likely to have occurred prior the time of sampling, the 3-day antecedent precipitation is computed by applying weights of 0.5,1.0, 1.0, and 0.5 to the total precipitation on the day of sampling and the three preceding days. This reflects an assumed 50% chance that rainfall occurred on the day of sampling after the sample was collected.

land uses. In Figure B-5, coliform counts are correlated with the total developed area (sum of agricultural and urban land uses). This model is simpler and fits the data equally as well. Geometric-mean dry-weather fecal coliform counts increase from < 5 cfu/100 ml to >25 cfu/100 ml as upstream land development increases from 10% to 60%. Wet-weather counts increase from < 5 cfu / 100 ml to > 70 cfu / 100 ml as development increases from 10% to 60%. Results indicate that for a fully developed watershed, the geometric mean concentration would exceed 120 cfu / 100 ml. Based upon the ratios of arithmetic to geometric means in Table B-2, the arithmetic mean (which would be proportional to the loading or numbers of organisms reaching the Reservoir) would be exceed 5 times the geometric mean or 600 cfu/ 100 ml.

Figures B-4 and B-5 show one outlier ("Swamp 15") that was not included in the regression analyses. It had significantly higher fecal coliform levels than the other stations, when adjusted for differences in land use. This may be attributed to data limitations; this station was sampled in only one year and had a total of 35 samples, compared with a range of 50 to 263 for other primary and secondary stations (Table B-1). Otherwise, the high counts may reflect natural sources of fecal contamination that are also of concern from a water-supply perspective.

Data from primary stations are combined to estimate an average fecal coliform concentration for all inflows to the Reservoir from the watershed in Table B-2. To reflect differences in flow volumes across stations, the arithmetic mean concentration is weighted by total drainage area above each station. The average inflow concentration is 83 cfu/100 ml, more than 4 times the 20 cfu/100 ml Class-A standard. For individual tributaries, the average inflow concentration ranges from 46 cfu/100 ml (Quinapoxet River) to 299 cfu/100 ml (West Boylston Brook). When watershed inflows are diluted with Quabbin inflows, the average inflow concentration for all flow sources is estimated at 41 cfu/100 ml, still more than twice the standard. Because fecal coliform counts are positively correlated with flow at some stations (MDEP & MDC, 1994, MDC, 1998, p 2-3), flow-weighted-mean inflow concentrations (proportional to loading) are likely to exceed the above estimates (Walker, 1981). The average inflow concentration would also be much higher during extended periods of high runoff, when tributary concentrations are higher and inflows of relatively clean water from Quabbin Reservoir are lower.

5.3 Cosgrove Intake Fecal Coliform Data

Figure B-6 shows daily fecal coliform concentrations measured by the MWRA and MDC at the Cosgrove Intake between 1994 and 1999 in relation to the 20 cfu/100 ml standard. The data are summarized in Table B-4. The bottom panel of Figure B-6 shows the 6-month rolling-average frequency of samples exceeding 20 cfu/100 ml based upon data from each agency. Based upon MWRA's data, EPA's limit for a filtration waiver (<10%) was exceeded in 1999 and nearly exceeded (>9%) in 1996 and 1998. Although daily values decreased after January 1999, the 6-month rolling frequency remained above 10% at least through mid May 1999. Based upon MDC's data, the limit was exceeded in each year except 1997.

Fecal coliforms were detected by the MWRA on 66% of the sampling dates and exceeded the 20 cfu/100 ml standard on 3.5% of the dates. According to MWRA data, a concentration of 113 cfu/100 ml, more than 5 times the 20 cfu/100 ml standard, occurred on January 4, 1999. As discussed below, a large storm event occurred on the previous day. More than half of the samples collected by the MWRA in January 1999 exceeded the 20 cfu/100 ml standard. Regardless of the precise source of the organisms, these results indicate a risk of fecal contamination and the potential for pathogens entering the MWRA water-supply system.

Some of the apparent difference between MWRA and MDC results may be attributed to differences in sampling location (from a tap inside the Intake vs. from the reservoir surface in the vicinity of the Intake). Results in Figure B-6 use outside samples only on days when inside samples were not available. The MWRA results are based upon 1306 inside and 6 outside samples, where as the MDC results are based upon 164 inside and 1028 outside samples (Table B-4). Based upon a comparison of inside and outside results from either agency on dates when both types of samples were collected, outside fecal coliform counts exceed inside counts by an average of 27% ± 2 %.

No reduction in fecal coliform levels would be expected as the water passes through the intake into the pump station. The apparent difference between inside and outside samples may reflect the fact that outside samples are collected at the reservoir surface, whereas the intake structure is located >30 feet below the surface. Because of thermal stratification and density currents through the reservoir, vertical variations in water quality would be expected in some seasons (FTN & CDM ,1995). This would not explain differences throughout the year, however. Although the MDC's coliform results are somewhat higher, my analysis focuses on MWRA samples because these have been used in reporting satisfaction of the filtration avoidance criterion.

Fecal coliform spikes at the Cosgrove Intake and exceedences of the EPA's filtration waiver limit have been attributed to impacts of gulls roosting on the surface of the Reservoir (MDC, 1998). The limit in 1990-1993 (MDC, Figure 2-9a). The MDC attributes the decline in levels after 1993 (MDC, Figure 2-9B) to gull-control measures that were initiated around that time. In April 1993, however, the MWRA started reporting compliance using inside samples (MDC, Figure 2-9b). Based upon the above comparison of samples collected inside and outside of the Cosgrove Intake, it is possible that some of apparent reduction in fecal coliform counts after 1993 was due to this change in sampling protocol, as opposed to the gull-control program.

In the documents reviewed (Appendix C), I did not find any statistical analyses of the relationship between intake fecal coliform counts and gull populations (or gull control measures). The evidence appears to be generally anecdotal (Scannel et al., 1994), rather than scientific (i.e. based upon hypothesis testing). The MDC commissioned the University of Massachusetts to conduct extensive field studies, statistical analyses, and modeling of factors contributing to variations in fecal coliform counts in the vicinity of the Quabbin Reservoir intake (Tobiason et al.,1996, 1998). Given the greater immediate significance and risk of fecal contamination in Wachusett Reservoir, it is surprising that the MDC has apparently not funded a similar intensive study there.

According to the MDC (1998, p. 2-53), "Bacteria from tributaries do not appear to reach the intake in either the Wachusett or Quabbin Reservoirs". This notion is not only absurd from a common-sense perspective but it is also contra-indicated by MDC and MWRA monitoring data. Fecal coliforms were detected in 66% of the MWRA samples and 74% of the MDC samples at the Cosgrove Intake between 1994 and 1999. Although the winter peaks may be partially related to seasonal gull populations, coliforms were frequently detected throughout the year. If bacteria from the tributaries do not reach Cosgrove Intake, what is the source of the detected bacteria throughout the spring, summer, and fall months when gull populations are much reduced? Although coliform and pathogen loads would be attenuated somewhat in the reservoir as a result of natural die-off processes, it is unreasonable to expect that the reservoir would "sterilize" all contaminated inflows, particularly during the winter when die-off rates are lower because of low water temperatures and low light intensities (Chamberlain, 1985; Tobiason et al., 1996, 1998).

Significant increases in flow and fecal coliform concentrations have been observed in tributaries during and following storm events (MDC, 1998, CDM, 1999). Storms generate pulsed loadings of bacteria and other contaminants to the Reservoir. If bacteria from the watershed are transported through the reservoir, increases in bacteria concentrations may be observed at the Intake following storm events. A storm pulse would be attenuated as it moves through the reservoir because of dilution by Quabbin inflows and direct rainfall on the Reservoir surface, dispersion (mixing with Reservoir water), and die-off mechanisms. While each of these mechanisms would tend to cause a decrease in the peak bacteria concentration, only the last one would provide a net decrease in the number of organisms reaching the intake. Increases in fecal coliform concentration at the Intake following storm events would be a strong indication that some portion of the tributary bacteria loads are transported through the reservoir. This hypothesis is tested below.

The highest fecal coliform concentration reported by the MWRA between 1994 and 1999 was 113 cfu/100 ml on January 4, 1999 (Figure B-6). A large storm occurred on the previous day, with total precipitation of 1.19 inches measured by NOAA(1999) at Worcester airport and 0.99 inches measured by the MDC at Wachusett Reservoir (file hyd_1997.mdb Appendix C). Airport records indicate that this storm involved a mixture of rain, freezing rain, and snow, while the MDC reported rain only. Relatively low bacteria die-off rates would be expected in the Reservoir at this time or year because of cold water temperatures and low light intensities (Chamberlain, 1985). Although based upon a single event, these observations are consistent with the hypothesis that storm-driven pulses of fecal coliform loads from the watershed are transported through the Reservoir to the Intake. The observations also suggest that watershed loads of pathogen indicators contributed to exceedence of the filtration avoidance criterion in 1999 (Figure B-6).

To test further for a storm response at the Intake, I paired each MWRA sample with the total precipitation measured on the previous 3 days. I divided the data into three categories based upon antecedent precipitation (0.0-0.2, 0.2-1.0, and >1.0 inches). Table B-5 and Figure B-7 show the geometric mean and arithmetic mean concentrations in each precipitation category. For comparative purposes, I summarized watershed monitoring data in the same fashion, pooling all results from primary (reservoir inflow) stations. Both at watershed stations and at the Intake, fecal coliform concentrations increase significantly following storm events. At watershed stations, the arithmetic mean increases from 72 cfu/100 ml during dry weather (0-0.2 inches) to 350 cfu/100 ml following large storms (> 1 inch). At the intake, the mean increases from 3.1 cfu/100 ml during dry weather to 5.2/100 ml following large storms.

I tested the statistical significance of these results by performing an Analysis of Variance (ANOVA, Snedocor & Cochran, 1989) on the log-transformed data (Table B-5). For both data sets, I rejected the null hypothesis (no relationship between precipitation and bacteria) at a significance level $(p) < 0.001$, or confidence level > 99.9%. This means that it is highly unlikely that precipitation and fecal coliform counts are unrelated. As a check, I computed correlation coefficients (Snedocor & Chochran, 1989) between individual paired observations from the Intake using both log-transformed (r=0.11) and ranked data (r=0.10). Although the correlation coefficients are low (indicating the precipitation explains an small percentage of the total variance in the data), they are significantly greater than zero ($p< 0.001$).

Figure B-8 shows the storm response measured in terms of frequencies of measurements greater than 1, 2, 5, 10, 20, and 100 cfu/100 ml. Compared with means, frequency statistics are more robust to the presence of outliers or unrepresentative samples in the data set (Helsel & Hirsch, 1982; Gilbert, 1987). A steady increase in exceedence frequencies with antecedent precipitation is evident both at the watershed stations and at the Intake.

The combined effects of seasonal variations and precipitation on fecal coliform counts at the Intake are shown in Figure B-9. I placed the samples into categories defined by month and antecedent precipitation and computed geometric means and frequencies > 2 cfu/100ml within each category. Higher counts in winter months may reflect impacts of gulls and/or lower organism die-off rates within the Reservoir attributed to lower water temperatures and light intensities (Chamberlain, 1985). The wet-weather exceeded the dry-weather geometric means in each month of the year. I performed a two-way ANOVA (Snedocor & Cochran, 1989) on the log-transformed data and found that both the seasonal and the precipitation effects are significant at $p < 0.001$ (Table B-6). The precipitation response throughout the year is a strong indication that gulls are not the only source of fecal coliforms at the Intake.

The combined effects of yearly variations and precipitation on fecal coliform counts at the Intake are shown in Figure B-10. I placed the samples into categories defined by year and antecedent precipitation and computed geometric means and frequencies > 2 cfu/100 ml within each category. A two-way ANOVA (Table B-6) indicates that both yearly and precipitation effects are significant at $p < 0.001$. Wet-weather geometric means exceeded dry-weather values in each year. Higher values in 1999 partially reflect seasonal factors because the data set for that year includes only January-May. The relatively strong storm response in 1999 suggests that storms may have contributed to exceedence of the filtration-avoidance criterion in that year (Figure B-6).

I tested the sensitivity of these results to (a) data set (agency / sample location); (b) duration of antecedent precipitation period; (c) source of climatologic data; and (d) separation of rainfall from snowfall events. Results (Table B-8) are similar and do not change my conclusions. A storm response was detected for antecedent precipitation periods up to about 14 days. Over longer time frames, the signal would be dampened because storm pulses would overlap for periods exceeding the average time between storm events and because of mixing processes within the reservoir.

I interpret these results as a strong indication that storm-driven pulses of pathogen indicators are transported through the Reservoir to the Cosgrove Intake. Concentrations are lower and the precipitation response is less dramatic at the Intake, as compared with the watershed stations, because of the storm pulse is dampened as it moves through the reservoir. The fact that precipitation explains a small percentage of variance does not diminish the importance of the apparent storm signal detected at the Intake. The impact of watershed inputs on fecal coliforms at the Intake is likely to be greater than that reflected by the difference between the dry-weather and wet-weather results (Figure B-6). Dry-weather inputs from the watershed, as well as storm pulses dispersed in the Reservoir over periods longer than the typical time between storm events would contribute to the dry-weather measurements.

The 1-14 day response time can be compared with estimated transport times for Quabbin diversions or storm flows from the Stillwater River (most remote tributary) moving as density under-currents to the Intake (10-30 days, MDC,1998, FTN & CDM, 1995). Watershed inflows entering the surface of the Reservoir are transported at various speeds and directions, depending upon wind, and eventually entrained into the density current that moves to the Intake. During fall, winter, and spring periods when the Reservoir is not vertically stratified, circulation is driven by variable wind conditions. As a consequence of variations in circulation and the spatial distribution of tributary inflows, the water leaving the Reservoir at any particular time is likely to have a wide distribution of residence times. That is, a portion of the flow might have spent only a few days in the Reservoir, while another portion might have spent several months.

In studies of Quabbin Reservoir, Tobiason et al. (1996) measured surface current velocities that averaged 3.3% of the wind speed. Under a 20 mph wind, the current velocity would be 0.66 mph. At this rate, the travel time along the 6-mile main axis of the reservoir would be only 9 hours. The potential for rapid transport of watershed inflows to the Intake would be high under a strong downstream wind during periods when the Reservoir is not stratified, as indicated by the simulated current pattern for April 17, 1990 (FTN & CDM, Figure 6-23, p 6-53). Given potential rapid transport in local wind-driven surface currents and the spatial distribution of tributary inputs around the reservoir, it is not unreasonable to expect that intake fecal coliform levels could increase at the intake over relatively short time scales in response to watershed inputs. Although the precise tributary source(s) cannot be identified, these results are sufficient to reject the notion that bacteria loads from the watershed do not reach the intake and that gulls were the only source of fecal coliforms detected in 66% of the samples at the Cosgrove Intake between 1994 and 1999.

6.0 Pathogen Transport through the Reservoir

The presence of fecal coliforms at the Intake and their response to storm events suggests that pathogens of fecal origin (e.g., protozoans, enteric viruses) are also transported through the Reservoir, especially considering the fact that many of these organisms are more persistent in the environment (die-off less rapidly) than fecal coliforms (Barker, 1998; Chamberlain, 1985). Pathogen transport through the reservoir is confirmed by their detection at the Intake (Clancy, 1999). The half-life (time for 50% reduction) of fecal coliform populations in natural waters is generally in the range of a few hours to several days (Chamberlin, 1985; Tobiason et. al, 1998). Within this range, longer halflives are associated with lower water temperatures and lower light intensities. Survival of protozoan pathogens is generally reported on a scale of months. Roberts et al. (undated) cite a study performed by Gerba (1995) indicating a half life on the order of one month for Giardia and eight months for Cryptosporidium in cold water (4 degrees C). Daniel et al. (1996) reported that Cryptosporidium oocysts are resistant to adverse environmental factors and can survive for months under optimum environmental conditions. Clancy (1999) reported that oocycts can survive for months in moist, cool soil environments and in water, especially at low temperatures.

Particle settling rates in natural waters depend primarily on particle diameter and density. Rates also increase with water temperature (Fair et al., 1968). Because of small cell size and low specific gravity (Medema et al, 1998), Giardia cysts and Cryptosporidium oocysts are likely to have low settling velocities. Typically, 90% of the suspended solids in urban runoff has a settling rate exceeding 0.9 cm/hr (USEPA, 1986; Stahre & Urbonas, 1990; Walker, 1990). Medema et al. (1998) measured settling velocities of 0.5 cm/hr for Giardia and 0.13 cm/hr for Cryptosporidium and stated: "The observed sedimentation velocities are low and will probably not result in significant sedimentation in natural aquatic habitats. Turbulence caused by water flow, wind, temperature, and movement of aquatic organisms is more likely to influence the movements of oocycts in water than gravitational settling".

Medema et al. (1998) also reported that settling of Cryptosporidium was enhanced by attachment of cells to larger particles in a secondary wastewater effluent. There is no basis for extrapolating their results to the Wachusett watershed situation, however. They also note that sedimentation is reversible: "Since Oocysts have a high survivability, settling of Oocycts may result in accumulation in aquatic sediments. Disturbance of these sediments by bathers, ships, or increased water flow, may give rise to high concentration peaks in the water, yielding a relatively high risk of exposure for bathers or breakthrough through drinking water treatment systems." In a reservoir, wind and wave action can be added to the list mechanisms that cause resuspension of protozoans and other fine particles and subsequent transport to the Intake.

The time scales of protozoan die-off and settling are long in relation to the 10-30 day travel-time estimate for Quabbin diversions or storm flows from the Stillwater River moving as cool density under-currents to the Intake (MDC,1998, FTN & CDM, 1995). As discussed above (Section 5.3), wind-driven surface currents can also promote rapid transport under certain conditions. These comparisons indicate that Reservoir should not be relied upon to provide significant reductions of pathogenic protozoans. It would be better to rely on water treatment by filtration, a process that typically reduces protozoan pathogen concentrations by a factor 100 or more, while removing other contaminants associated with fine particles (Nieminski, 1997).

7.0 Comments on Protozoan Data

Rose (1999) & Clancy (1999) discuss the limitations of Cryptosporidium and Giardia data as bases for evaluating health risks associated with these pathogens and making management decisions. I offer a few additional comments from a statistical perspective.

The MWRA(1998) presents data indicating 3 positive results for Cryptosporidium out of 81 samples collected at the Intake between March 1995 and March 1998 and 0 positive results out of 50 samples collected between November 1996 and March 1998. Even if the individual sample results were accurate, these data would have low "information content", primarily because of the limited number of samples and the high inherent temporal variability of microbial populations. Large numbers of samples are required to detect spikes in microbial populations that may occur at low frequencies. For example, if spikes occur at a 1% frequency (3-4 days per year), the probability of detecting one or more spike in 50 total samples would be only 39%, based upon the binomial distribution (Snedocor & Cochran, 1989). This means that there would be a 61% chance of obtaining a misleading "clean slate" (no detections in 50 samples). If the number of samples is increased from 50 to 100, the probability of detecting at least one spike increases from 39% to 63%, still not very good odds. At least 300 samples would have to be collected in order to be 95% sure of detecting at least one spike when the actual spike frequency is

1%. Spikes occurring less frequently are even more difficult to detect. This situation requires high-frequency sampling to evaluate current status and to track long-term trends.

High detection limits is another factor limiting the value of the Cryptosporidium data. For example, in 57 protozoan samples collected at the Cosgrove Intake (file epadb.mdb, Appendix C) between February 1994 and April 1999, the detection limit exceeded 1 organism/100 liters in 79% of the samples and exceed 10 organisms/ 100 liters in 39% of the samples. Corresponding frequencies in 30 samples collected after November 1996 were 63% and 10%, respectively. Organisms present in samples at concentrations below the detection limits would show up as non-detects. The reported detection frequencies may significantly under-estimate the actual frequencies of occurrence. This problem is compounded by the limitations in the analytical procedures discussed by Clancy (1999) and Rose(1999).

Another statistical limitation of the protozoan monitoring data for Wachusett tributaries relates to the fact that they are based upon grab samples collected monthly or biweekly without regard to flow. This sampling method is unlikely to capture pulse loads associated with storm events. In studies of the Delaware River at Trenton, New Jersey, Atherholt et al. (1998) found sharp increases in the concentrations of total and fecal coliforms, E-Coli, Enterococci, Giardia, and Cryptospordium during and immediately following rainfall events. Stewart et al. (1997) compared grab samples with samples collected from a device designed to capture the "first flush" following storm events in two California watersheds. In 20 grab samples, the Cryptosporidium detection frequency was 19% and the organism concentrations ranged from 3.4 to 647 oocysts/100 liters. In 21 first-flush samples, the detection frequency was 35% and the concentration ranged from 46 to 41,666 oocysts/100 liters. This suggests that average concentrations and detection frequencies reported in Wachusett watershed samples (MWRA, 1998) could significantly under-estimate the actual values. Similar limitations may exist in the routine fecal coliform monitoring data (Appendix B), which were also based upon grab samples.

8.0 Roles and Limitations of Watershed Management

MDC's intensive watershed management program is essential for protecting source water quality, regardless of the treatment scheme that is implemented. MWRA(1991) states: "Even with filtration, improved watershed protection is clearly needed to protect the quality of the source water. Watershed protection will serve to limit to a minimal acceptable level the presence of those pollutants which are removable by the planned filtration scheme, as well as prevent those chemical contaminates which cannot be handled by filtration from entering the waters supply source in the first place."

In a recent issue of Watershed Protection and Management focusing on controlling bacteria in urban watersheds, the Center for Watershed Protection (CWP,1999, pp.551) states: (1) "Even a small amount of (watershed) development leads to almost continuous violations of bacteria standards". This statement is clearly supported by fecal coliform monitoring data from the Wachusett Watershed. CWP (1999, pp. 552) also states "Bacteria are highly resistant to the watershed approach". This a telling statement from an organization that has been on the forefront of developing technical guidance for designing Best Management Practices (BMP's) to control a wide array of urban runoff pollutants. CDM & FTN (1984, p. ES-3) indicate that "Even after in-watershed mitigation, tributaries discharge a significant amount of coliforms to the reservoir. Little data exist to define what happens to bacteria once they are in the reservoir." The wide array of protection and management practices that have been and are being implemented by the MDC may be effective to some degree. However, there is a great deal of uncertainty in forecasting the effectiveness of individual practices and the combined effects of the entire program on a watershed scale, especially in the face of ongoing development.

Aggressive measures to reduce contaminant loads from existing agricultural and urban areas are typically required to offset the impacts of new development. For example, nutrient enrichment or "eutrophication" has been identified as a potential threat to Reservoir water quality (MDC, 1998). The increase in algal populations and organic matter caused by eutrophication can have several direct and indirect impacts on water supplies, including increased levels of taste and odor, increased disinfectant demand, increased trihalomethane precursors, interference with filtration and other treatment processes, and increased potential for bacteria re-growth in distribution systems (Walker, 1983; Walker et al.,1989). Export of phosphorus, the key nutrient of concern, from urban areas in the Northeast is typically 10-fold higher than export from undeveloped areas (Walker, 1982). Stormwater detention ponds required for larger developments under the Watershed Protection Act can be expected to remove 50-70% of the phosphorus load. (Walker, 1987). Thus, a 3-5 fold increase in phosphorus load would be expected for each acre of newly developed land, even with implementation of stormwater controls. A greater increase per acre would be expected for small developments with less restrictive control requirements. Benefits of controlling existing sources will be at least partially offset by impacts of new development. The situation is likely to be similar or worse for bacteria and pathogens, given the concept that "bacteria are highly resistant to the watershed approach" and given limitations and uncertainty in the performance of BMP's for controlling these organisms (CWP, 1999).

The feasibility of reducing contaminant loads in stormwater runoff from existing developed areas is limited from regulatory and technical points of view. Because of "grand-fathering" provisions in the Watershed Protection Act, the efficacy of the WSPA is limited (USEPA, 1999). The WSPA applies only to areas within stream buffer zones. As shown in Figure A-10, a considerable amount of development has already occurred in these areas. Proximity to streams and shallow water tables reduce the feasibility and effectiveness of structural BMP's (detention ponds, infiltration basins, buffer strips) potentially implemented to treat runoff (Schueler, 1987). Furthermore, BMP construction in these areas may involve collateral damage to wetlands, floodplains, and streams that may be unacceptable from a conservation or wildlife protection perspective. This illustrates potential conflicts between management of the watershed for water-supply vs. management for conservation and wildlife.

In its guidance manual for controlling non-point source pollution in coastal areas, the USEPA (1993) makes a clear distinction between BMP's applicable to existing developments and those applicable to new developments. BMP's identified as most applicable to existing developed areas (modified catch basins, oil/grit separators, modified flood control basins) are generally less effective than those applicable to new developments (detention ponds, filter strips, swales). Expected removal efficiencies are reported for a wide range of pollutants (suspended solids, nutrients, heavy metals), but not for bacteria or pathogens. This reflects lack of information on BMP performance for bacteria and pathogens and, hence, great uncertainty in forecasting effectiveness. The uncertainty bands in forecasting BMP performance are wide, even for contaminants that have been well-studied. For example, the USEPA(1983) cites a "probable range" of 10 to 60% for phosphorus removal in retrofitting urban flood control basins to provide treatment benefits.

The MDC has appropriately targeted the Gates Brook watershed (#38 in Figure A-2) for implementation of stormwater control measures and construction of sewers. The average fecal coliform concentration at the mouth of the watershed in 1994-1999 was 247 cfu/1000 ml, 25 times the Class A standard of 20 cfu/100 ml (Table B-2). This high concentration indicates a high risk of contamination with pathogens of fecal origin, as confirmed by detection of Giardia and Cryptosporidium at this site (MWRA,1998; file epadb.mdb, Appendix C). Gates Brook discharges directly into the Reservoir. Stormwater controls being considered for this watershed include an "in-lake" treatment device consisting of a baffled area in the Reservoir at the mouth of the Brook (ENSR, 1998; CDM, 1999). The design concept is to isolate the inflow from the Reservoir for a period of time to allow settling and other treatment processes to occur before the water enters the open Reservoir. The intended function is similar to that of detention ponds that are typically constructed immediately downstream of developments. Preliminary field tests indicate that the device is partially effective in removing total suspended solids (ENSR, 1998).

ENSR(1998, p 20) recommended against establishing a specific treatment goal for bacteria, stating: "Except for perhaps sand filtration, disinfection, and chemical coagulation, there are few, if any, technologies that will substantially reduce (90% or greater) bacteria concentrations in runoff." In other words, stormwater treatment devices cannot be considered substitutes for conventional water treatment, including filtration. ENSR (1998, p. 20) continue with: "There are multiple sources of observed bacteria including both domestic and animal (pets, livestock, and wildlife) waste in the Gates Brook Watershed. Data does not exist to determine the relative contribution of these various sources." Given that the sources have not been distinguished and given the uncertainty in forecasting BMP performance, there is currently is no quantitative basis to forecast the net benefits of control measures being implemented in the Gates Brook or other Wachusett subwatersheds measured in terms of bacteria, pathogen, or other contaminant loads, especially in the context of ongoing development.

Based upon my experience with a similar device in a project for the St. Paul Water Utility, in-lake treatment devices employing flexible baffles are difficult to maintain, frequently leak, and can be readily destroyed by high winds or shifting ice cover. If the structural integrity of the device can be maintained, limited removal of fecal coliforms may be achieved under low and average flow conditions. CWP(1999) cites average removals of 65% for fecal coliform and 51% for E. coli in stormwater detention ponds. It is likely that performance will be significantly diminished during periods of high runoff, when stream bacteria concentrations tend to be highest (CDM, 1999) , when water residence time in the baffled area is short, and when water temperatures may be low. Even if a 65% load reduction in fecal coliforms could be achieved, average concentration entering the reservoir from Gates Brook would be as much as ~4 times the 20 cfu/100 ml standard, depending upon the effectiveness of other control measures being implemented in the watershed.

One limitation of detention BMP's results from the fact that bacteria can survive for long periods and even multiply in the bottom sediments of urban drainage systems (CWP, 1999). Bacteria or pathogens removed by sedimentation in the Gates Brook treatment device or other detention ponds being considered for other subwatersheds (CDM, 1999) could be resuspended during periods of high flow, wind, or other sediment disturbance (Medema et al, 1998; Reilly, 1999). Accumulated sediment would be flushed into the reservoir if the in-lake device fails.

The most important limitation of detention BMP's is that they cannot be relied upon to remove fine particles with low settling velocities or protozoans with long survival times. CWP(1999) states: "It is thought that stormwater practices will have difficulty in removing Giardia and Cryptosporidium". This statement reflects lack of specific performance data as well as the long survival times and low setting rates for these organisms (Section 6).

Detention ponds are typically designed with average water residence of 7-14 days (Schueler, 1987; Walker, 1987). The Thomas Basin, a segment of the Reservoir at the mouths of the Quinapoxet and Stillwater Rivers which discharges to the main Reservoir through culverts under Route 12 (Figure A-2), also has an average detention time in the 7-14 day range. Residence times in detention ponds and in Thomas Basin would be much lower during high runoff periods. The MDC (1998, p2-19) suggests that Thomas Basin, functions as "an effective detention and sedimentation basin" for treatment of watershed inflows. This statement does not apply to protozoan pathogens with low settling rates and survival times typically reported in terms of months (Section 6). Existing data indicate that detention BMP's and Thomas Basin, like the Reservoir itself, cannot be relied upon as barriers against persistent pathogens and other contaminants associated with fine particles.

While the control measures being considered under the Stormwater Management Plan (CDM, 1999) seem reasonable and appropriate, I believe that the BMP performance assumptions (Table 3-5) used to forecast the benefits are overly optimistic. The report does not adequately convey the wide uncertainty bands around these predictions. Some of the performance assumptions are in direct contradiction to other data presented in the report and to opinions expressed by other MDC consultants. The assumed fecal coliform reductions in Table 3-5 (90-95%) are inconsistent with values shown in Table 2-7 (50-90%). A 95% reduction in fecal coliform loads is attributed to in-lake treatment at 3 locations. This is in direct contradiction to ENSR's (1998, p 20) statement cited above. On p. 3-10, CDM states that other BMP's were assumed to have characteristics similar to the generalized "Ponds" category in Technical Note 95 (CWP, 1997). The bacteria removal ascribed to ponds in Technical Note 95 is 65%, yet CDM assumes a 90% fecal coliform removal in Table 3-5. The 95% reduction in fecal coliform loads attributed to agricultural BMP's and the 100% reduction attributed to a diversion BMP are extremely optimistic.

9. Rebuttal to MWRA Expert Reports.

In his Expert Report (June 1999), Marco Aieta concludes that there "appears to be no correlation between storm events, storm flows, and coliform positive samples at Cosgrove intake (Appendix H - Precipitation Impacts)". In his Rebuttal Report (July, 1999), Phillippe Daniel also concludes that there is no significant correlation between fecal coliform counts at Cosgrove Intake and antecedent precipitation. I have reached precisely the opposite conclusion. The fact that Aieta and Daniel have been asked to conduct this analysis supports my opinion that the relationship between intake fecal coliform counts and antecedent precipitation is relevant to evaluating risk of pathogen transport from the watershed, through the reservoir and into the MWRA supply system.

A wide variety of statistical procedures can be applied to test hypotheses based upon monitoring data (Snedecor & Cochran, 1989; Helsel & Hirsch, 1982). Depending upon characteristics of the data, some methods are more appropriate than others. Aieta and Daniel have elected to use a linear correlation method that both is both inappropriate and weak, given the highly skewed distributions and strong seasonality in the data. By "inappropriate", I mean that basic assumptions of the test are violated. By "weak", I mean that, of the wide variety of methods that could be applied, Aieta and Daniel have selected a method that would be least likely to detect a correlation, even if basic assumptions were not violated. I am not at all surprised that they did not find a correlation, since it is clear that they did not look very hard.

The direct linear correlation method is inappropriate because the data are not normally distributed ("bell-shaped") and effects of precipitation are obscured by extraneous factors (e.g., seasonality, gull influences, and management actions to control gulls). At a minimum, log-transforming the data prior to the analysis is necessary to reduce the skewed nature of the data distribution and promote a more bell-shaped distribution which is more appropriate for application of the correlation method.

By electing to combine all of the data from 1990-1999, Aieta and Daniel have considered two periods with very different winter-time fecal coliform levels, possibly attributed to implementation of gull-control measures after 1993 (see third figure in Aieta's Appendix H). This has the effect of amplifying the "noise" in the data and decreasing the probability of detecting the precipitation "signal". Since the MWRA has emphasized post 1993-data to support its highly questionable decision not to build a filtration plant, I believe that it is most appropriate to focus the data analysis on the post-1993 period.

Scatter plots of fecal coliform data in Aieta's Appendix H and total coliform data in Daniel's Attachment B are highly misleading because the high frequency of low counts at low precipitation values cannot be discerned. With Aieta's graph scale (0 to 700 cfu/100 ml) it is obviously impossible to discern any information about the frequency of fecal coliform detection (percent of measurements >1 cfu/ 100 ml) or about the frequency of violations of the drinking water standard (percent of values > 20 cfu/100 ml). Linear correlation coefficients computed from this type of data tend to be unduly influenced by a few relatively high measurements, which may reflect gull impacts and/or unrepresentative samples, as well as storm events.

Aieta's analysis is also seriously lacking because he apparently considers only same-day or 1-day antecedent precipitation. Watershed runoff is more likely to be correlated with cumulative rainfall over a longer time frame. The same-day correlation is particularly absurd, since there is a high probability that many of the water quality samples would have been collected before the same-day storm events. In their analysis of watershed monitoring data, CDM (1999) used a 3-day total antecedent rainfall to distinguish wet and dry sampling periods. I have used a similar criterion.

It is puzzling that Daniel has elected to include numerous scatter plots of <u>total</u> coliform measurements in his rebuttal, but failed to include any <u>fecal</u> coliform plots, which are clearly more relevant.

I believe that it is appropriate to focus on the 1994-1999 data set because it reflects the status-quo. I have used five different procedures that I believe are more appropriate. and more powerful than Aieta/Daniels' to test the null hypothesis that there is no correlation between precipitation and intake fecal counts:

- One-way analysis of variance vs. precipitation
- Correlation based upon log-transformed data
- Correlation based upon ranks
- Two-way analysis of variance vs. precipitation & season
- Two-way analysis of variance vs. precipitation & year

In each case, I reject the null hypothesis at a "p" level less than 0.001 or 0.1%. This means that I can state with greater than 99.9% confidence that there was a positive correlation between Intake fecal coliform counts and antecedent precipitation over the January 1994-May 1999 period. I have tested the sensitivity of my results to a wide range of factors, including duration of precipitation, location of sampling, sampling agency (MDC vs. MWRA), and source of climatologic data, and have reached the same conclusion. Though the correlation coefficients are necessarily low because of the high background variability inherent in bacteria populations, they are positive and significant from statistical and management points of view. They clearly reflect a risk of pathogen transport from the watershed to the MWRA intake.

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Appendix A
Analysis of Watershed GIS Data

Data Sources

Coverage	**Source**
MDC Land Use	MassGIS (1999)
MDC Parcels	MassGIS (1999)
MDC WSPA Buffer Zones	MassGIS (1999)
Wachusett Watershed Boundary	MassGIS (1999)
Wachusett Subwatersheds	MassGIS (1999)
Roads, Railroads	MassGIS (1999)
Geology	MassGIS (1999)
Land Contours	MassGIS (1999)
Aerial Photos	Downloaded from MassGIS Web Site
TIGER Census Blocks	U.S. Bureau of Census (1990)
Monitoring Stations	Created by WWW from MDC Monitoring Maps, Appendix B

List of Tables

List of Maps

Table A - 1
Wachusett Watershed Land Use Inventory

Code	Description	Categ.	Total Acres	Percent of Total	Percent of Categ.	WSPA Buffer Zones Prim.	WSPA Buffer Zones Sec.	WSPA Buffer Zones Other	Protected Areas MDC	Protected Areas Other P	Protected Areas Total P
0	Unknown	Undev	2	0.0%	0.0%	0	0	2	0	0	0
1	cropland	Agric	2909	4.1%	53.9%	250	463	2196	441	1321	1762
2	pasture	Agric	1988	2.8%	36.8%	195	270	1522	402	635	1037
5	mining	Urban	291	0.4%	3.3%	21	109	160	15	48	63
6	open	Undev	2408	3.4%	4.2%	575	426	1406	733	759	1492
7	recreation - participati	Urban	193	0.3%	2.2%	29	34	129	18	61	78
8	recreation - spectator	Urban	10	0.0%	0.1%	1	2	7	1	0	1
9	recreation - water	Undev	7	0.0%	0.0%	1	2	4	0	2	3
10	multi-unit residential	Urban	143	0.2%	1.6%	20	44	79	0	2	2
11	dense residential	Urban	149	0.2%	1.7%	11	21	117	0	0	0
12	medium residential	Urban	1512	2.1%	17.3%	98	205	1209	9	15	24
13	light residential	Urban	4385	6.2%	50.2%	375	773	3237	64	230	294
15	commercial	Urban	303	0.4%	3.5%	56	81	167	4	7	10
16	industrial	Urban	152	0.2%	1.7%	38	74	40	4	12	16
17	urban open	Urban	160	0.2%	1.8%	16	32	113	14	6	20
18	transportation corridor	Urban	317	0.4%	3.6%	57	48	212	2	135	137
19	waste disposal	Urban	105	0.1%	1.2%	10	65	29	50	30	80
20	open water	Undev	1914	2.7%	3.4%	1866	13	35	417	1112	1529
24	powerline	Urban	368	0.5%	4.2%	78	59	232	152	41	193
31	urban public	Urban	216	0.3%	2.5%	38	25	152	20	38	58
32	transportation facility	Urban	41	0.1%	0.5%	13	12	15	3	0	3
34	cemetery	Urban	72	0.1%	0.8%	11	20	41	1	60	60
35	orchard	Agric	253	0.4%	4.7%	7	19	227	8	188	195
36	nursery	Agric	245	0.3%	4.5%	20	37	188	12	131	143
38	golf course	Urban	313	0.4%	3.6%	51	43	219	1	202	203
40	deep marsh	Undev	278	0.4%	0.5%	250	13	15	48	82	130
41	marsh	Undev	341	0.5%	0.6%	165	54	122	122	100	222
42	shrub swamp	Undev	528	0.7%	0.9%	286	119	123	122	150	272
43	bog	Undev	42	0.1%	0.1%	26	4	11	14	2	16
44	wooded wetland - deci	Undev	3282	4.6%	5.8%	1327	951	1005	1076	960	2036
45	wooded wetland - coni	Undev	145	0.2%	0.3%	19	95	32	30	52	82
46	wooded wetland - mix	Undev	800	1.1%	1.4%	212	282	306	247	224	471
50	deciduous forest	Undev	27022	38.0%	47.4%	3932	3654	19436	7566	7490	15056
51	evergreen forest	Undev	9380	13.2%	16.5%	1737	1904	5740	3135	2752	5887
52	mixed forest	Undev	10774	15.2%	18.9%	1482	1729	7564	3202	3052	6255
88	not interpreted by DEF	Undev	26	0.0%	0.0%	10	0	16	20	0	20
Total			71072	#####		13282	11681	46109	17955	19898	37852
Totals by Category											
	Undevelope		56950	80.1%		11888	9245	35817	16733	16738	33471
	Agricultural		5394	7.6%		472	789	4133	863	2275	3138
	Urban		8728	12.3%		921	1647	6160	359	885	1244
	Total		71072	#####		13282	11681	46109	17955	19898	37852
Category Percentages											
	Undeveloped		80.1%			89.5%	79.1%	77.7%	93.2%	84.1%	88.4%
	Agricultural		7.6%			3.6%	6.8%	9.0%	4.8%	11.4%	8.3%
	Urban		12.3%			6.9%	14.1%	13.4%	2.0%	4.4%	3.3%
	Total		100.0%			#####	#####	#####	100.0%	100.0%	100.0%

Notes:

Data from mdc land use coverage, 1992-93 areal photos; categories assigned by www

Total watershed area excludes Reservoir surface.

Protection categories defined in MDC Watershed Protection Plan extracted from parcel database:

MDC	MDC or DEM Ownership (excluding reservoir surface)
Other P	Parcels in Chapter 61, 61A, 61B, or with Other Designated Open Space Ownership
Total P	Total Protected = MDC + Other

Table A - 2
Land Use Inventories by Subwatershed

Id	Name	Sanitary Distric	Agric	Urban	Undev	Total	Agric	Urban	Undev
			Acres				Percentages		
2	KEYES BROOK	STILLWATER	68	220	2918	3206	2%	7%	91%
3	JUSTICE BROOK	STILLWATER	146	127	2909	3182	5%	4%	91%
4	EAST WACHUSETT BROOK	STILLWATER	383	402	4921	5706	7%	7%	86%
5	ROCKY BROOK	STILLWATER	195	109	1646	1950	10%	6%	84%
6	DAVIS FARM/US FARM	STILLWATER	82	54	994	1130	7%	5%	88%
7	WORC/QUIN	WORCESTER	1095	657	10854	12606	9%	5%	86%
8	UPPER WAUSHACUM BROO	THOMAS BASIN	263	468	1670	2401	11%	20%	70%
9	WILDER BROOK	STILLWATER	153	134	544	830	18%	16%	66%
10	STILLWATER @ STEEL BRID	STILLWATER	309	297	849	1454	21%	20%	58%
11	BALL BROOK	STILLWATER	24	102	356	481	5%	21%	74%
12	TROUT BROOK	QUINAPOXET	327	241	3862	4430	7%	5%	87%
13	SCANLON BROOK	STILLWATER	99	96	635	829	12%	12%	77%
14	HOUGHTON BROOK	STILLWATER	176	95	391	662	27%	14%	59%
15	LOWER WAUSHACUM BROC	THOMAS BASIN	192	387	1110	1690	11%	23%	66%
16	HOG HILL	QUINAPOXET	81	50	817	948	9%	5%	86%
17	THOMAS BASIN/SHORELINE	THOMAS BASIN	101	86	883	1070	9%	8%	83%
18	GATE 36 TO 42	RESERVOIR	18	8	43	69	26%	12%	63%
20	GATE 26 TO 35	RESERVOIR	64	58	1334	1456	4%	4%	92%
21	LOWER QUINAPOXET	QUINAPOXET	66	129	1417	1612	4%	8%	88%
22	UPPER QUINAPOXET	QUINAPOXET	98	116	1349	1564	6%	7%	86%
23	OAKDALE	THOMAS BASIN	36	105	189	330	11%	32%	57%
24	GATE 1 TO 5	RESERVOIR	3	23	412	437	1%	5%	94%
25	MIDDLE QUINAPOXET	QUINAPOXET	76	276	774	1127	7%	24%	69%
26	BEAMAN POND	THOMAS BASIN	22	141	210	373	6%	38%	56%
27	WORC/PINEHILL/KENDALL	WORCESTER	616	535	4287	5438	11%	10%	79%
28	GATE 6 TO 16	RESERVOIR	41	30	752	824	5%	4%	91%
29	MALDEN BROOK	THOMAS BASIN	95	200	921	1216	8%	16%	76%
30	CRESCENT	THOMAS BASIN	3	75	90	167	2%	45%	54%
31	HASTINGS COVE BROOK	RESERVOIR	7	19	362	389	2%	5%	93%
32	ASNEBUMSKIT BROOK	QUINAPOXET	82	552	885	1520	5%	36%	58%
33	FRENCH BROOK	RESERVOIR	73	209	1093	1375	5%	15%	80%
34	GATE 17 TO 25	RESERVOIR	4	30	576	609	1%	5%	94%
35	WEST BOYLSTON BROOK	RESERVOIR	32	129	99	260	12%	50%	38%
36	EAGLE LAKE	QUINAPOXET	14	78	1215	1307	1%	6%	93%
37	SWAMP 15	QUINAPOXET	97	68	533	698	14%	10%	76%
38	GATES BROOK	RESERVOIR	111	676	858	1645	7%	41%	52%
39	LOWER CHAFFIN/UNIONVILL	QUINAPOXET	19	577	982	1578	1%	37%	62%
40	PINE HILL	RESERVOIR	7	38	85	130	6%	29%	65%
41	BOYLSTON BROOK	RESERVOIR	7	35	99	140	5%	25%	71%
42	SCARLETT BROOK	RESERVOIR	1	189	130	320	0%	59%	41%
43	POTASH BROOK	RESERVOIR	0	40	80	120	0%	33%	67%
44	MALAGASCO BROOK	RESERVOIR	52	120	390	562	9%	21%	69%
45	MUDDY BROOK	RESERVOIR	7	192	335	534	1%	36%	63%
46	DIAMOND HILL	RESERVOIR	9	31	142	182	5%	17%	78%
47	CHAFFIN POND	QUINAPOXET	41	525	1950	2516	2%	21%	78%
Total			5394	8728	56950	71072	8%	12%	80%

Summary by Sanitary District

	Agric	Urban	Undev	Total	Agric	Urban	Undev
QUINAPOXET	902	2614	13784	17300	5%	15%	80%
RESERVOIR	435	1826	6790	9051	5%	20%	75%
STILLWATER	1634	1635	16162	19430	8%	8%	83%
THOMAS BASIN	712	1462	5073	7247	10%	20%	70%
WORCESTER	1711	1192	15141	18044	9%	7%	84%
TOTAL	5394	8728	56950	71072	8%	12%	80%
TOTAL - Excluding Worcester District *	3683	7536	41809	53028	7%	14%	79%

* Approximate estimate of contributing watershed. Because of diversions to Worcester water supply, this District contributes flow to Wachusett Reservoir only during periods of high runoff. (CDM, 1999).

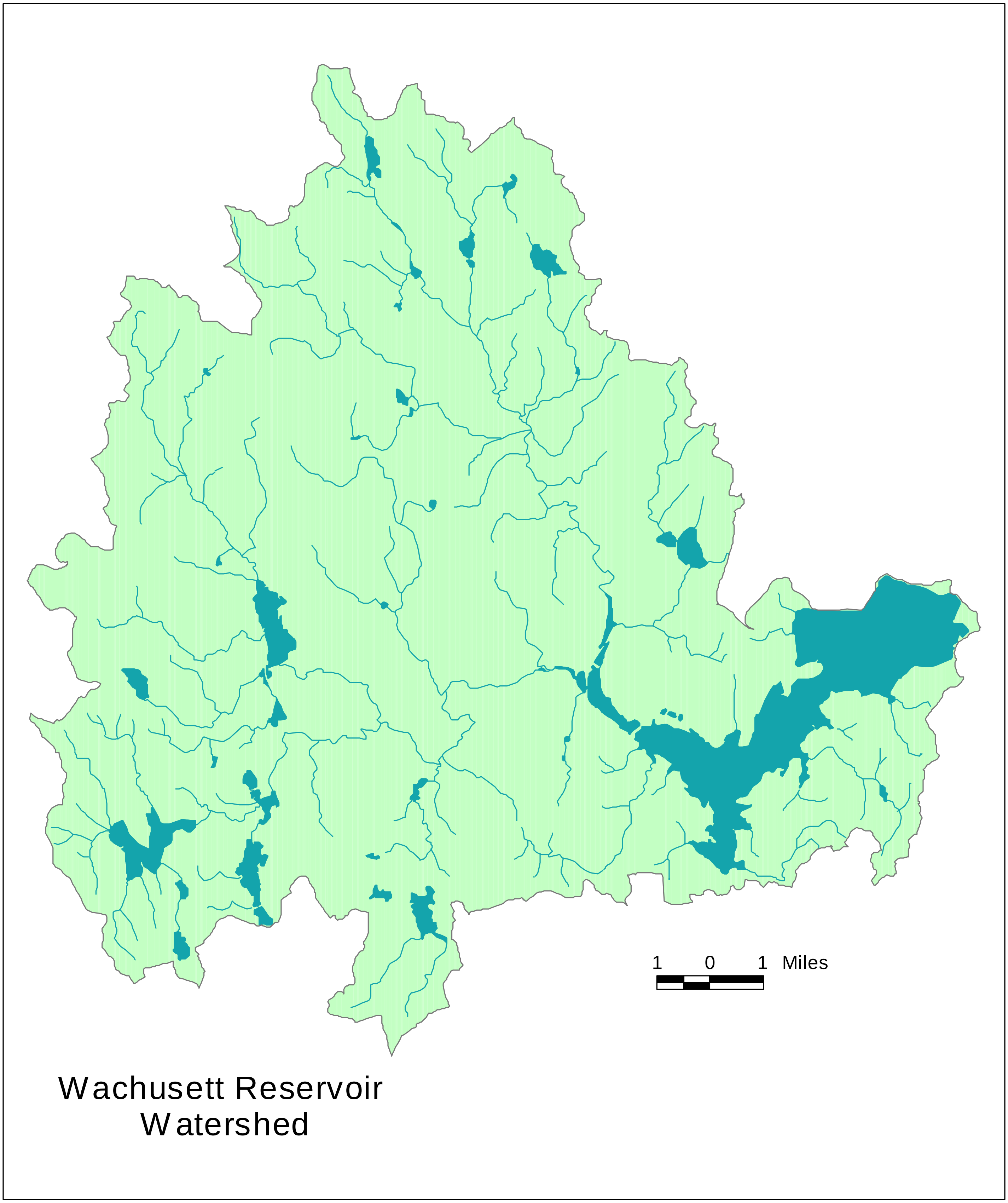
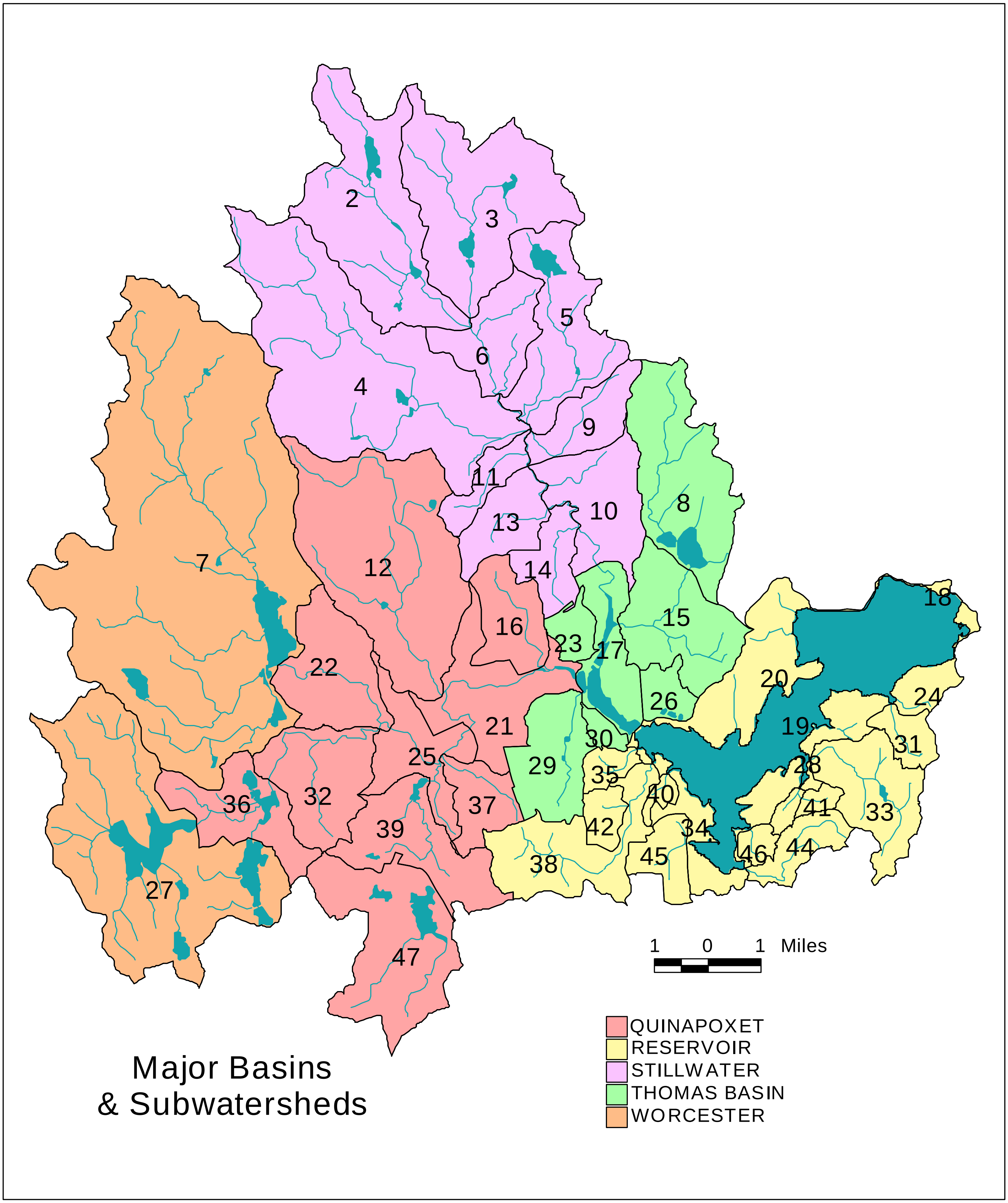


Figure A - 1



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Major Basins
& Subwatersheds

Figure A - 2

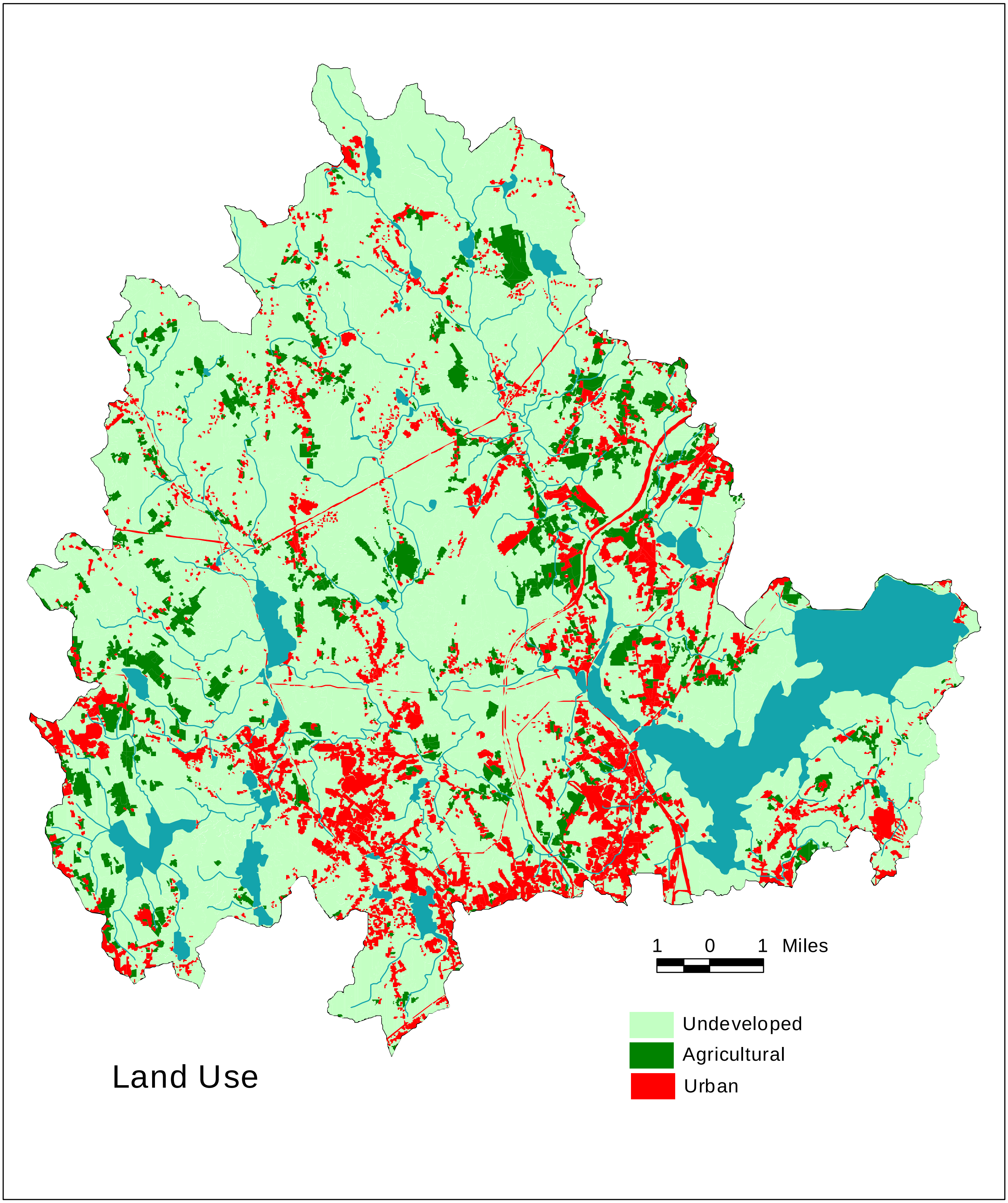


Figure A - 3

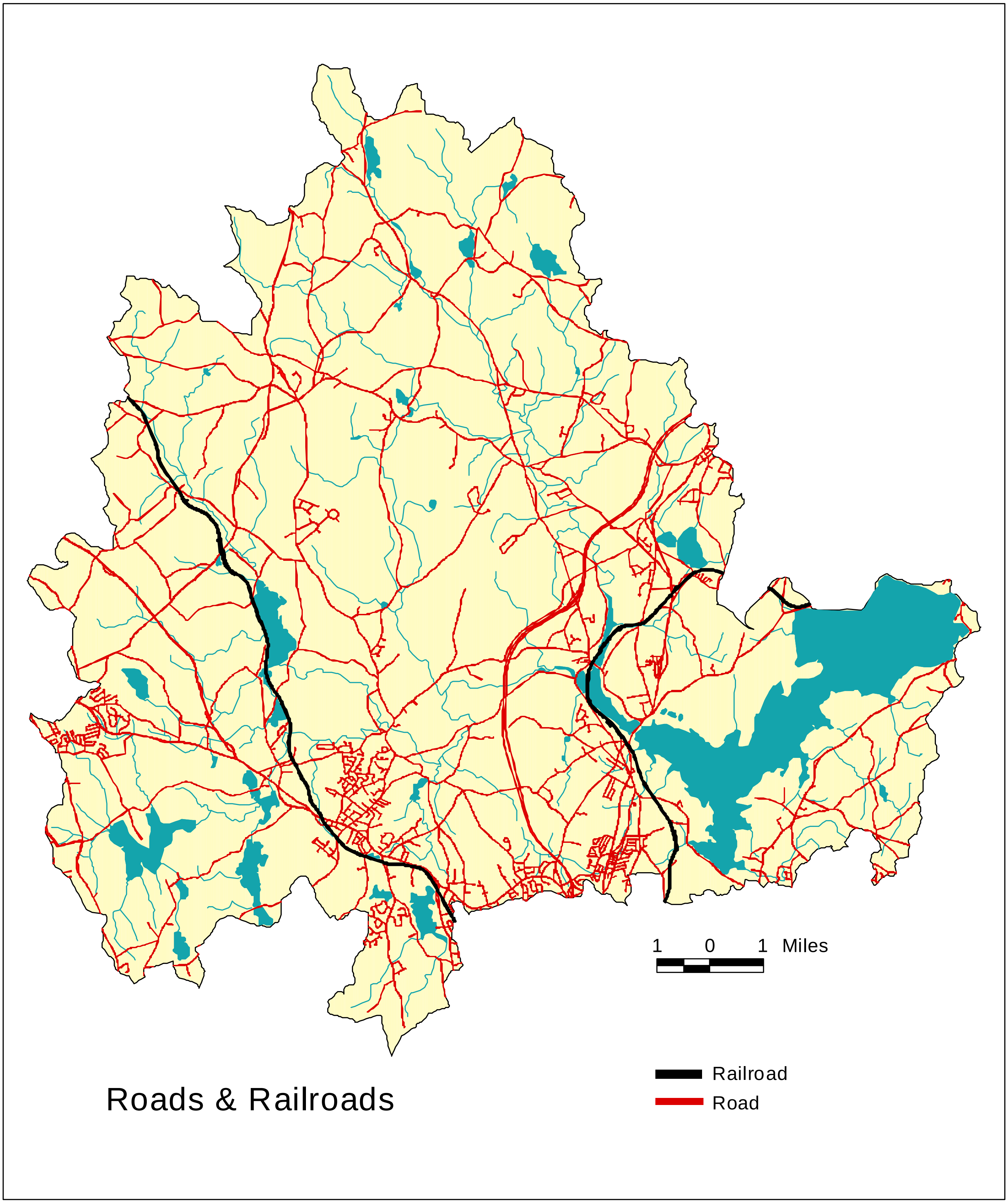


Figure A - 4

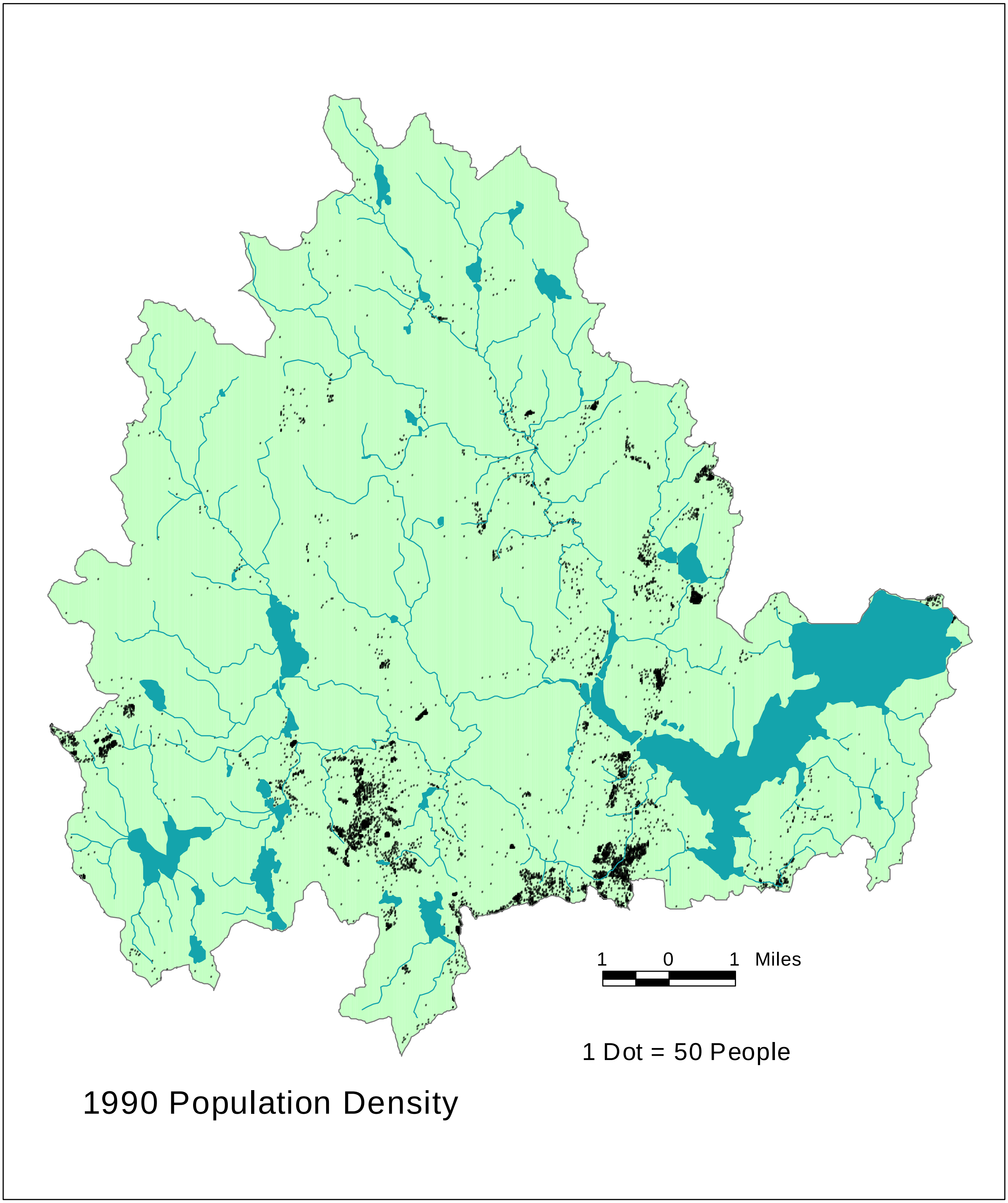
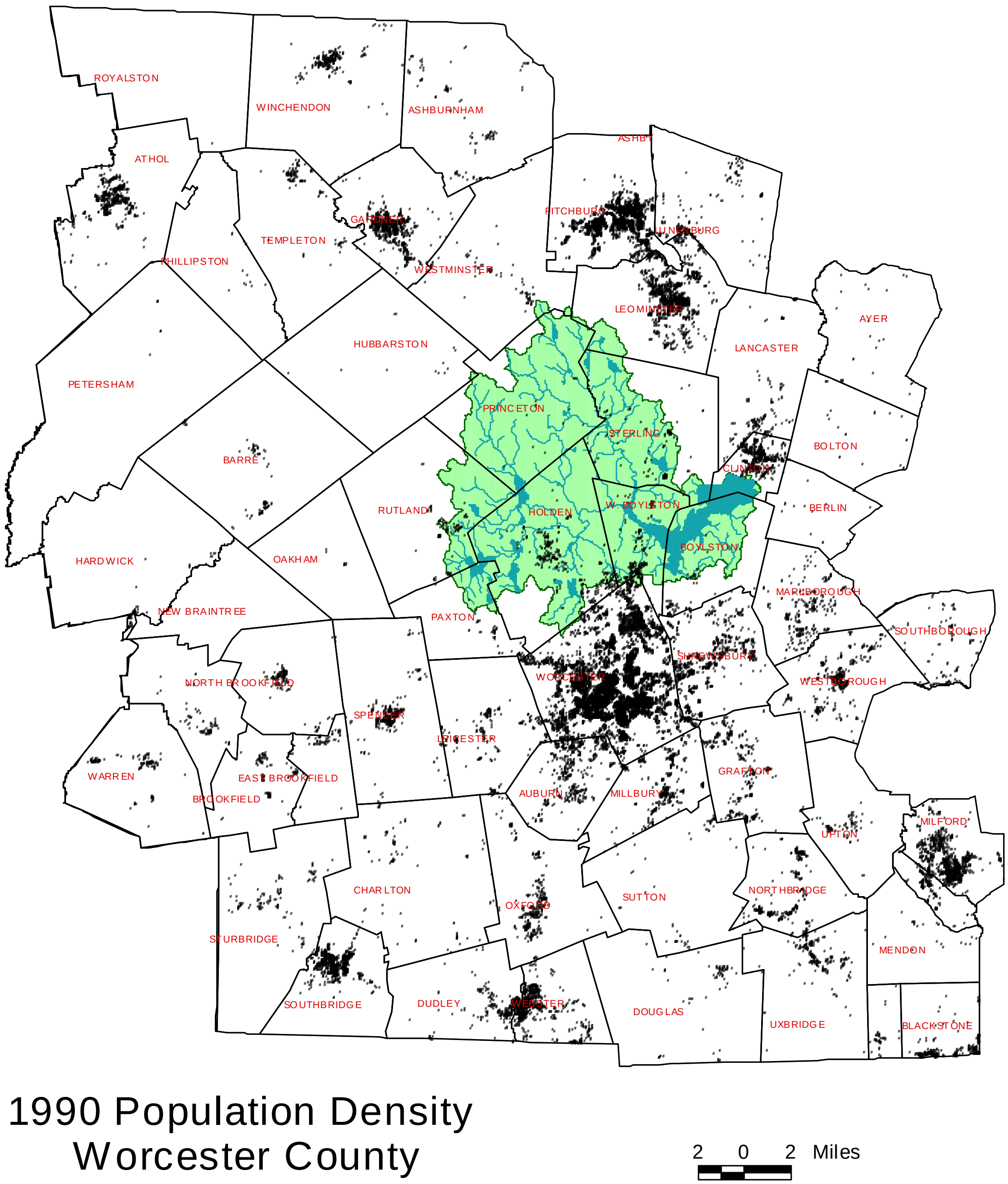


Figure A - 5



1990 Population Density
Worcester County
1 Dot ~ 500 People

Figure A - 6

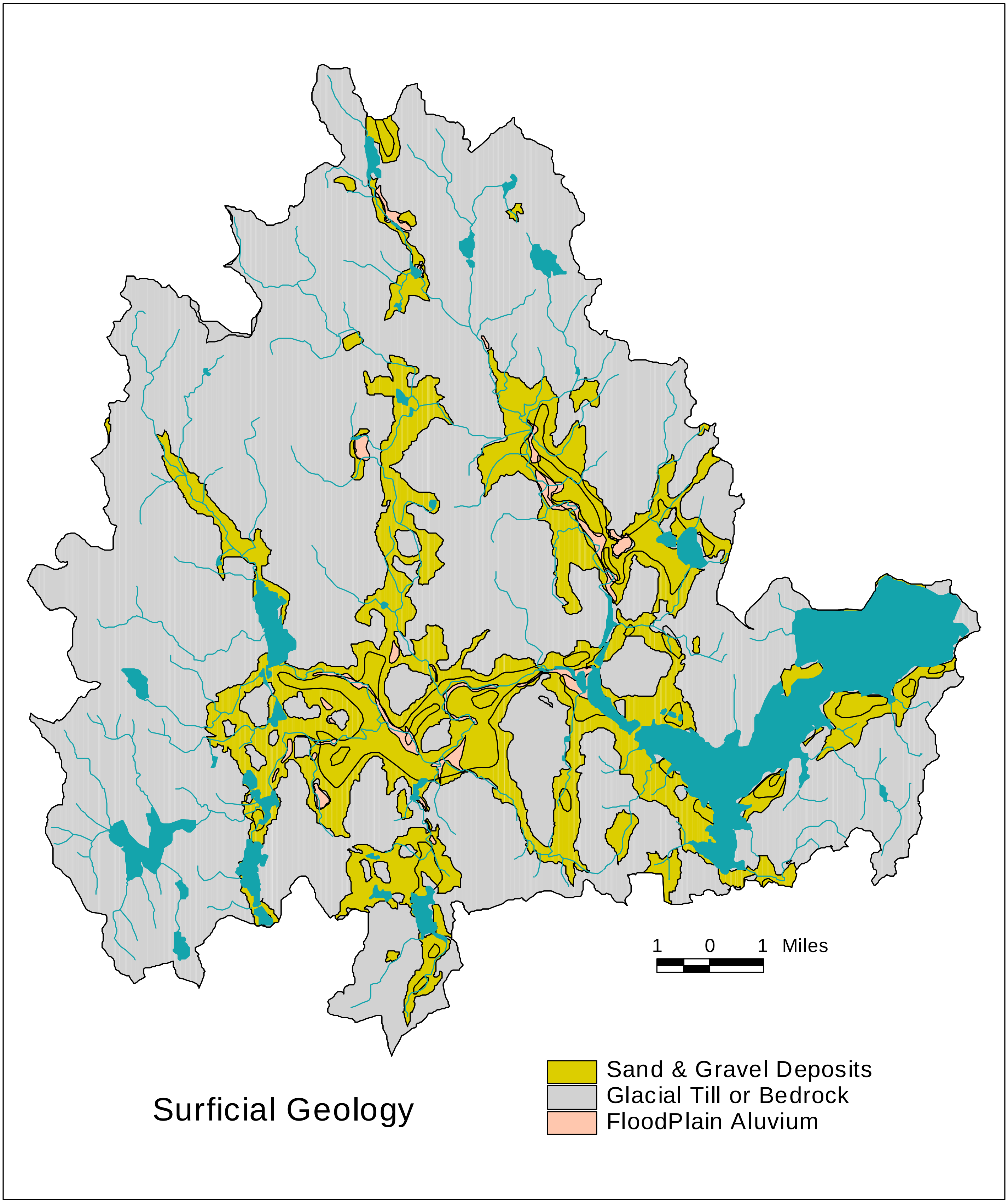

1 0 1 Miles
Sand & Gravel Deposits
Glacial Till or Bedrock
FloodPlain Aluvium
Surficial Geology

Figure A - 7

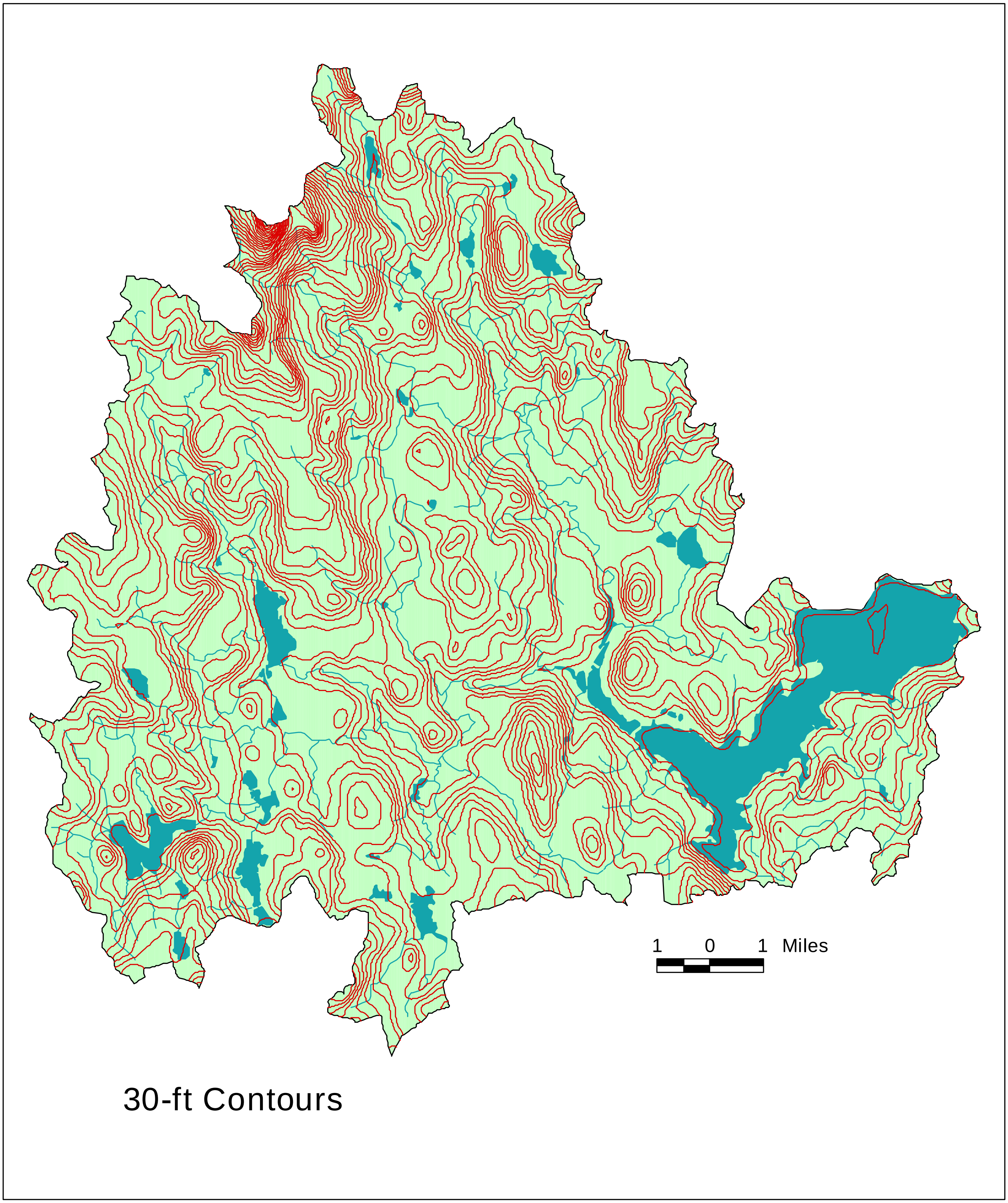


Figure A - 8

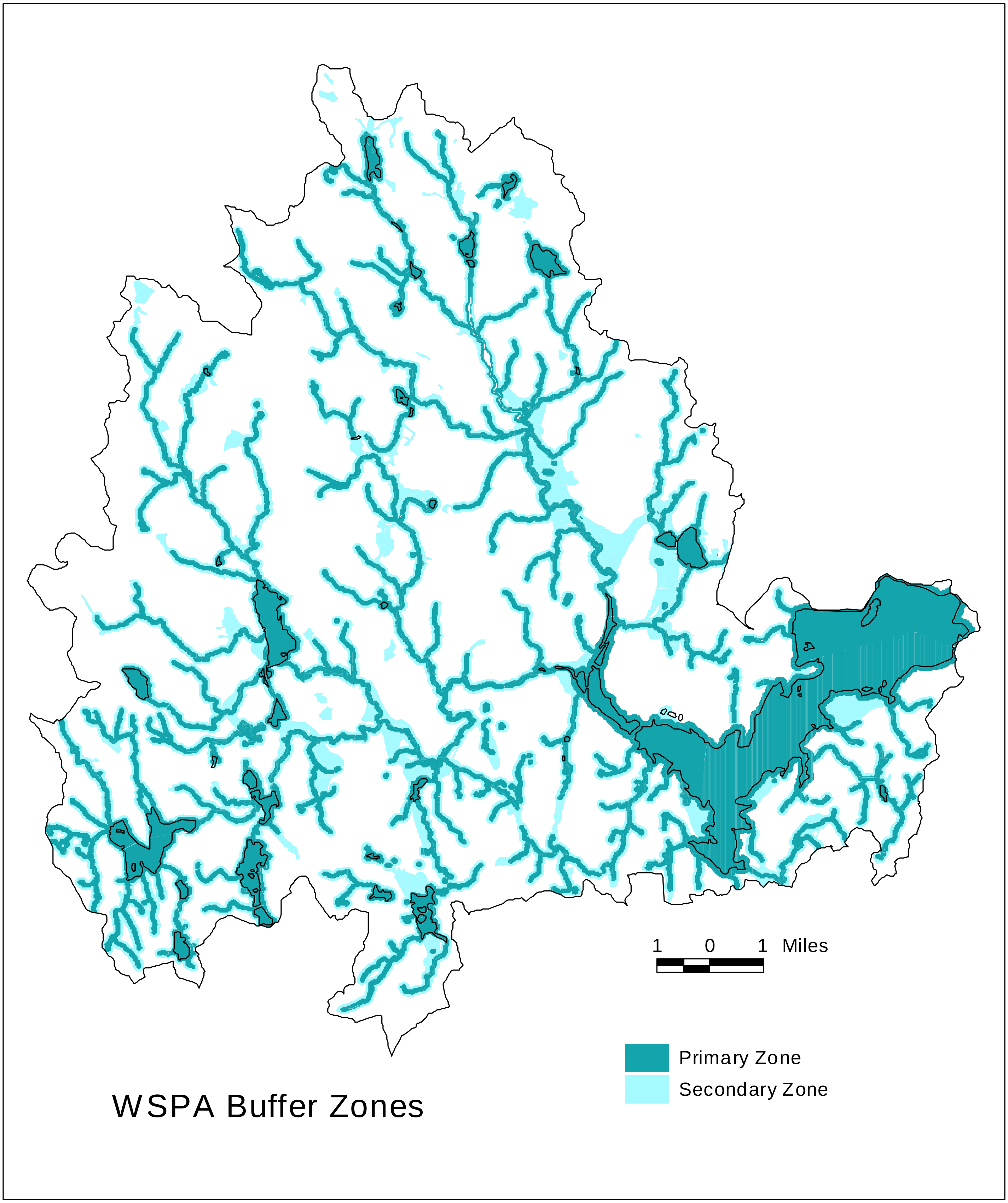


Figure A - 9

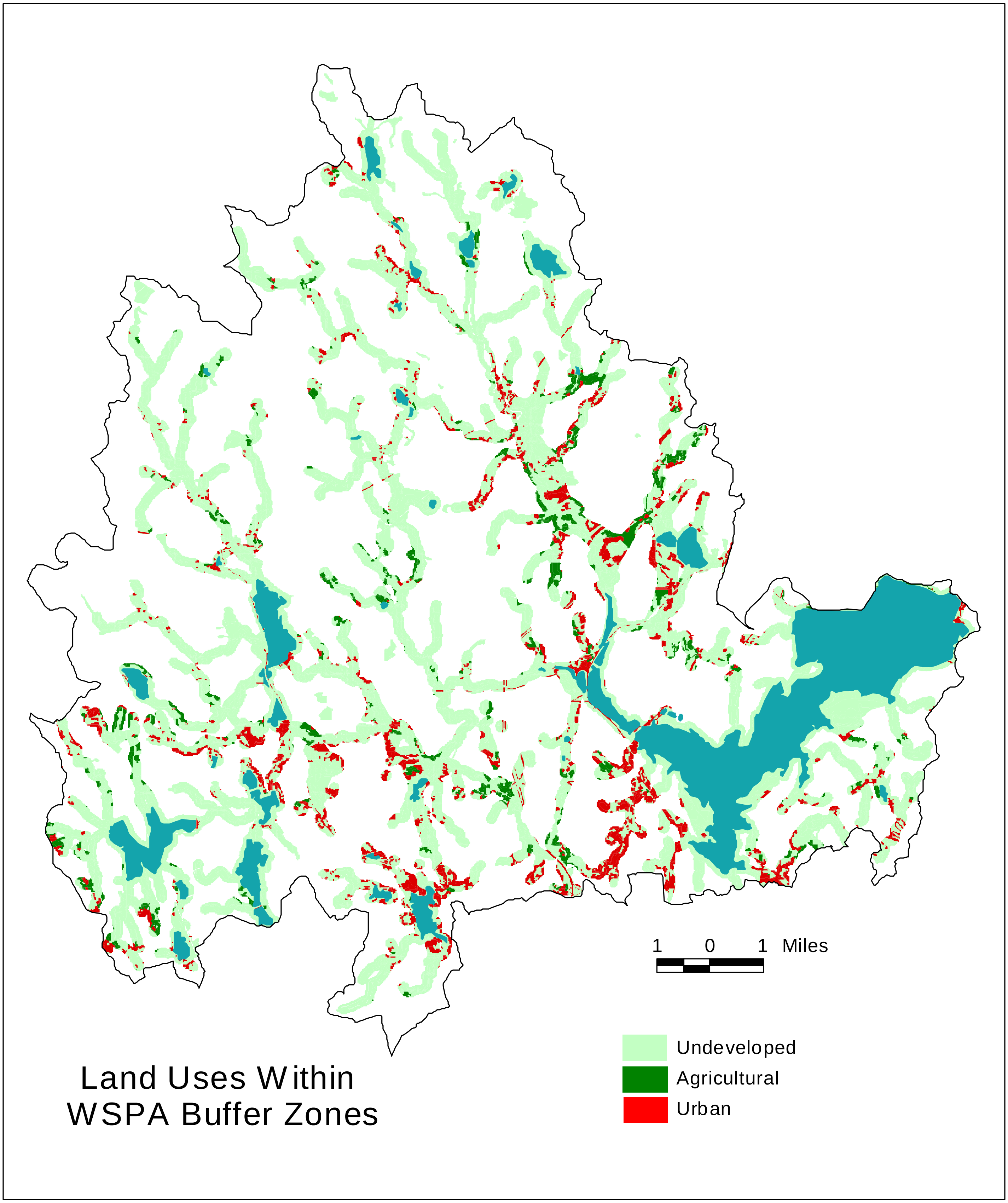

1 0 1 Miles
Undeveloped
Agricultural
Urban
Land Uses Within
WSPA Buffer Zones

Figure A - 10

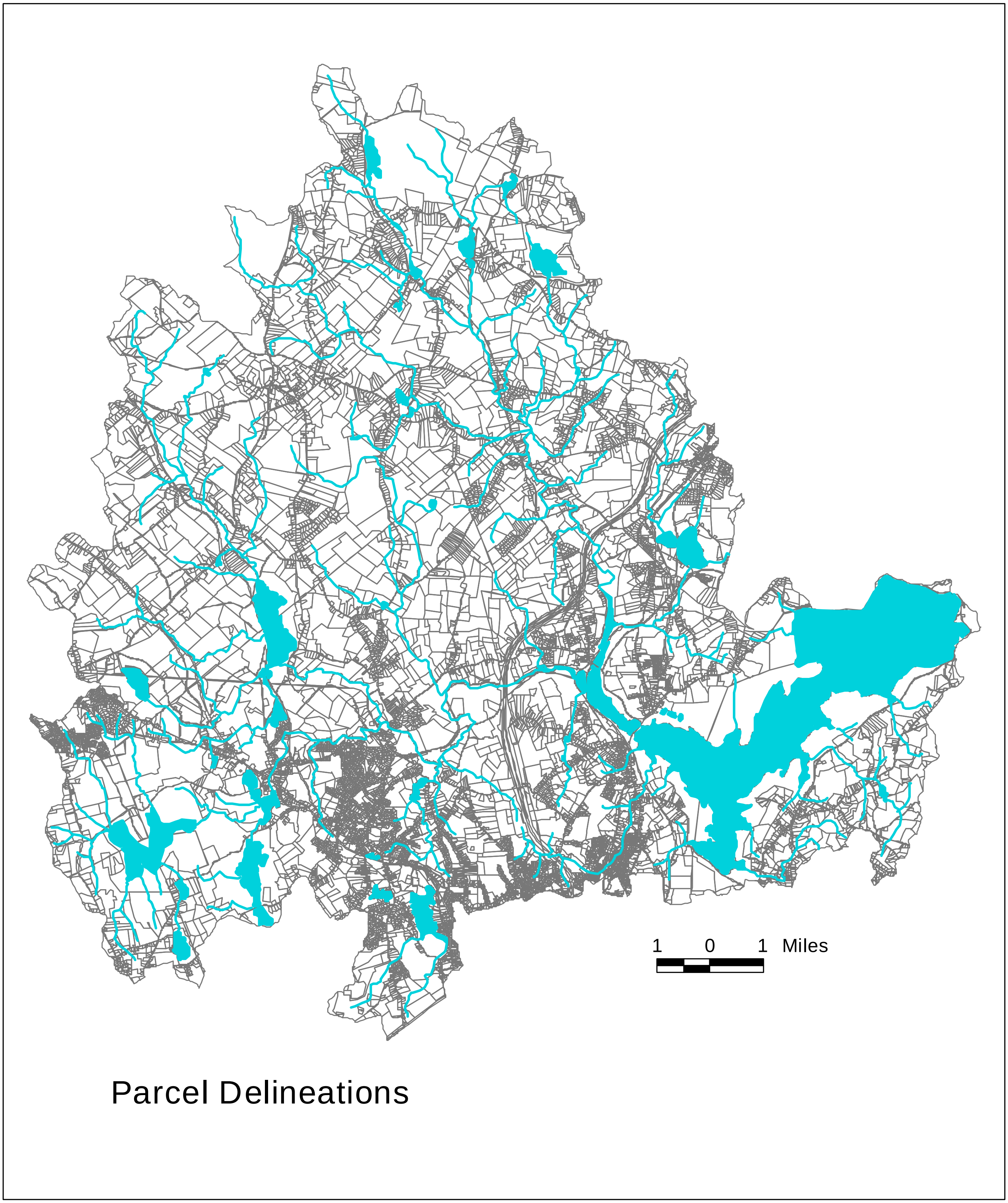


Figure A - 11

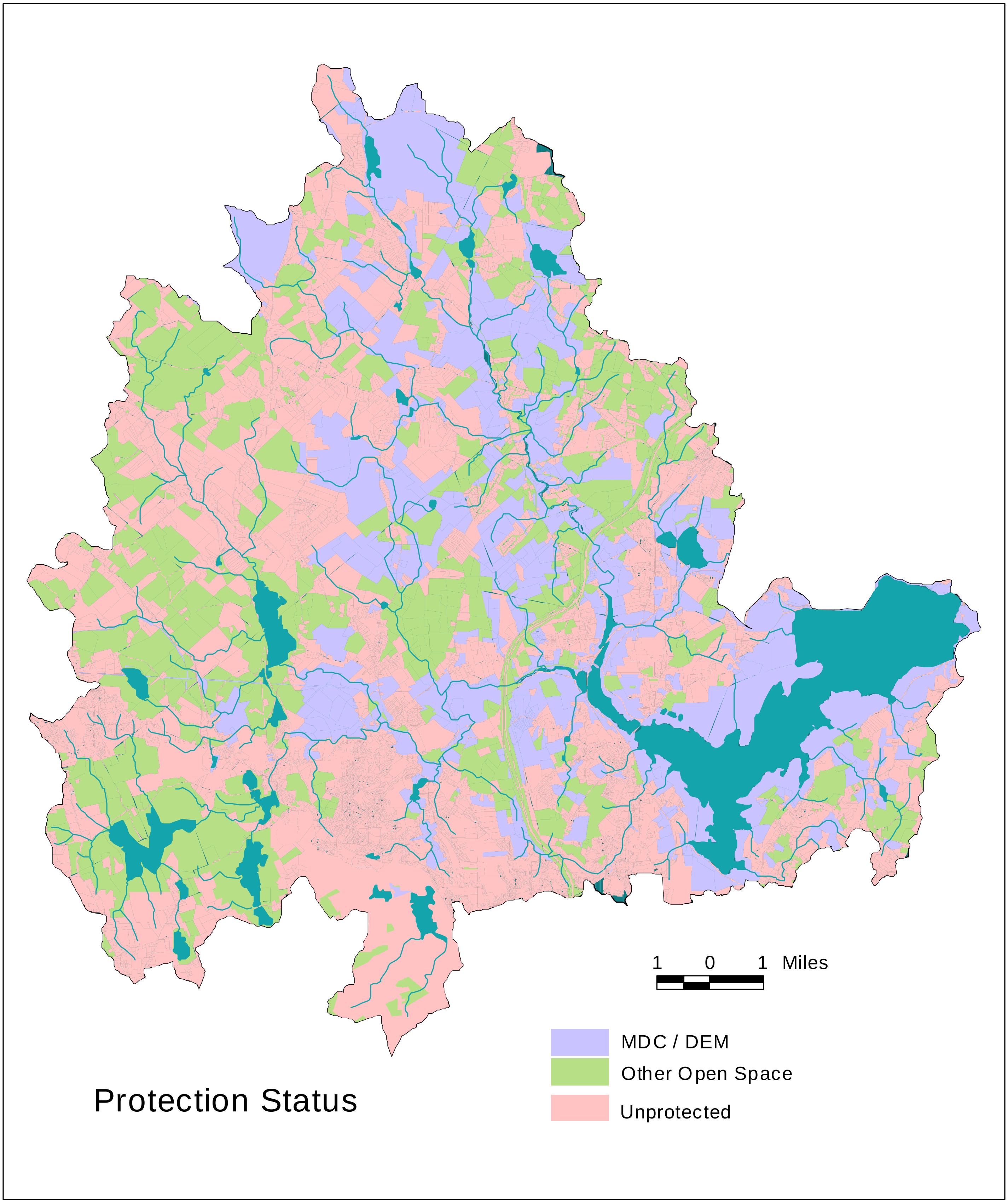

1 0 1 Miles
MDC / DEM
Other Open Space
Unprotected
Protection Status

Figure A - 12

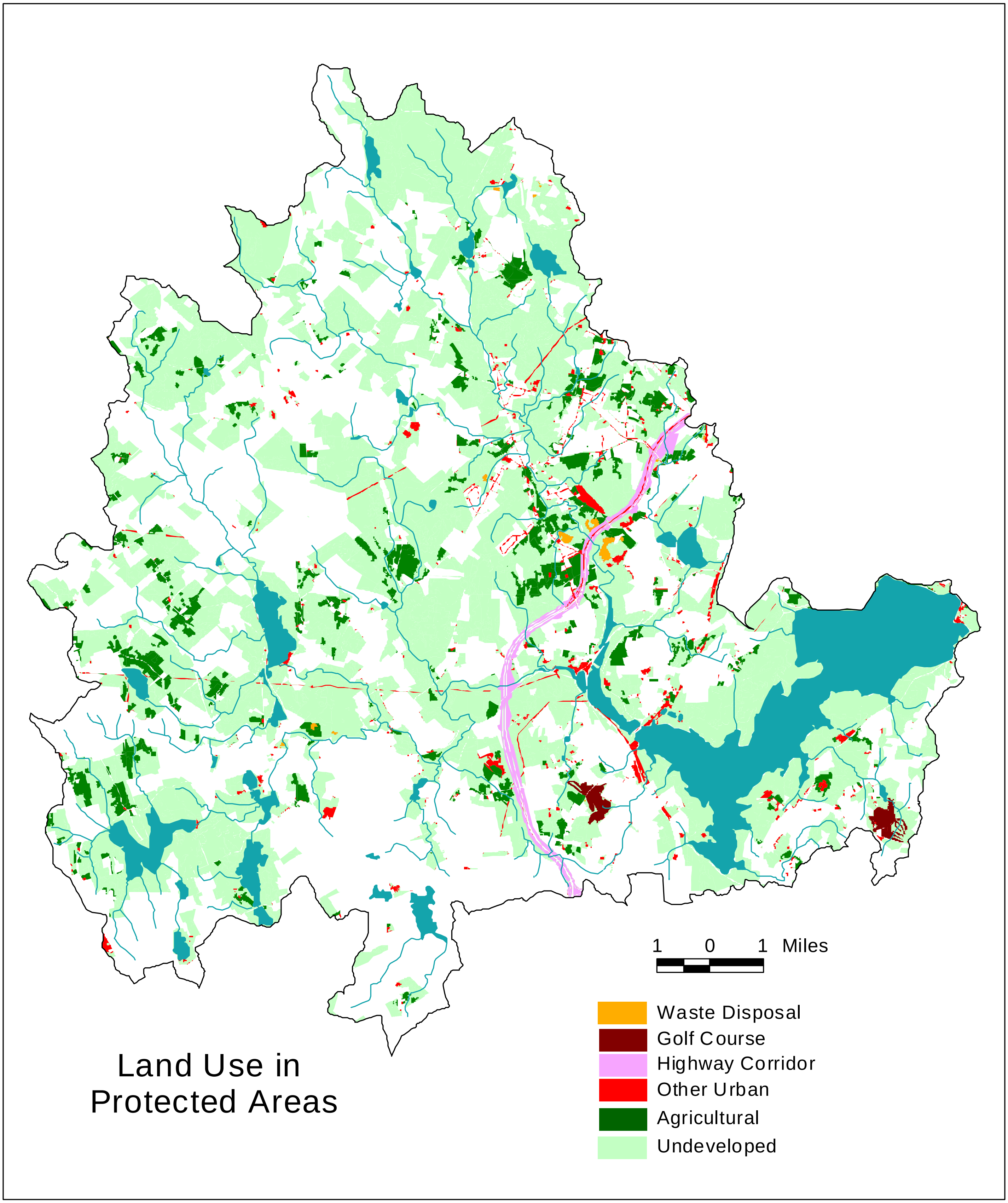

1 0 1 Miles
Waste Disposal
Golf Course
Highway Corridor
Other Urban
Agricultural
Undeveloped
Land Use in
Protected Areas

Figure A - 13

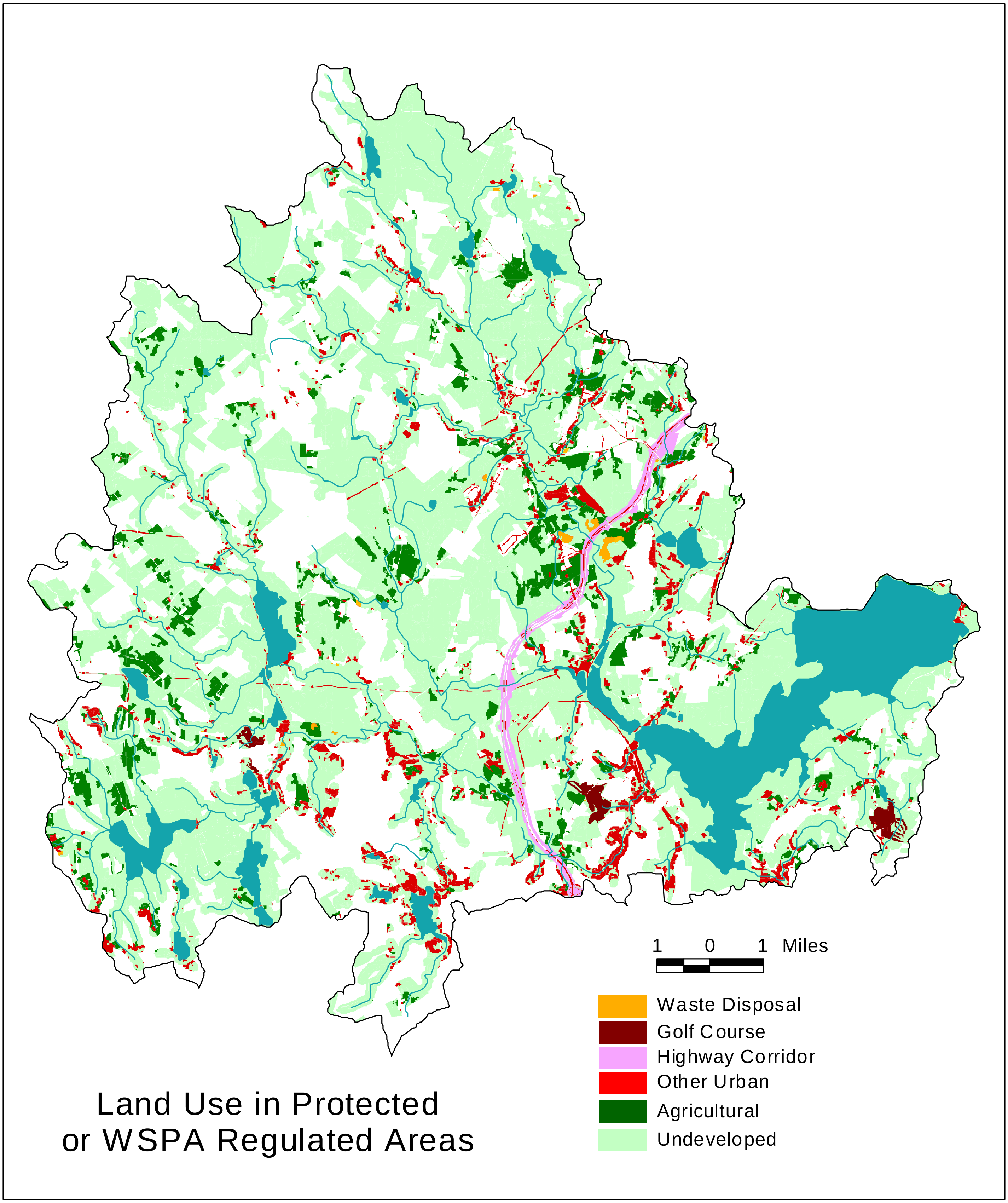
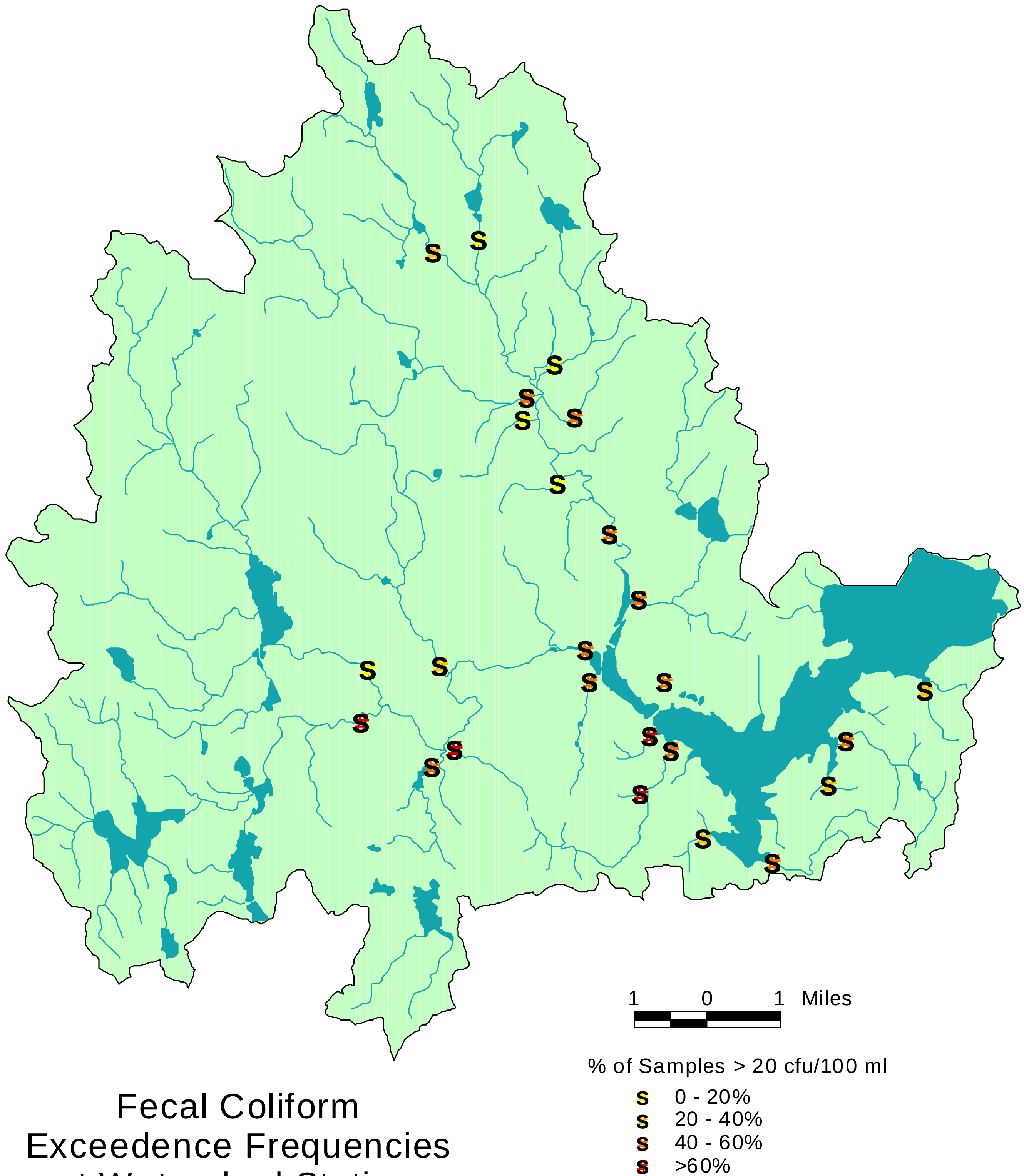

1 0 1 Miles
Waste Disposal
Golf Course
Highway Corridor
Other Urban
Agricultural
Undeveloped
Land Use in Protected
or WSPA Regulated Areas

Figure A - 14


Justice
Keyes
Rocky
E. Wachusett
Wilder
Ball
Scanlon
Houghton
Stillwater
Cosgrove
Intake
Wauschacum
Hog Hill
Quabbin Aq.
Quinapoxet (Mill)
Trout
Quinapoxet
Malden
Beaman Pond
Hastings Cove
Asnebumskit (Mill)
W. Boylston
Swamp 15
French
Gates
Asnebumskit (122A)
Chaffins
Scarlett
Boylston
Muddy
Malagasco
Eagle Lake
1 0 1 Miles
Primary
Secondary
Monitoring Stations

Figure A - 15



Fecal Coliform
Exceedence Frequencies
at Watershed Stations

Figure A - 16

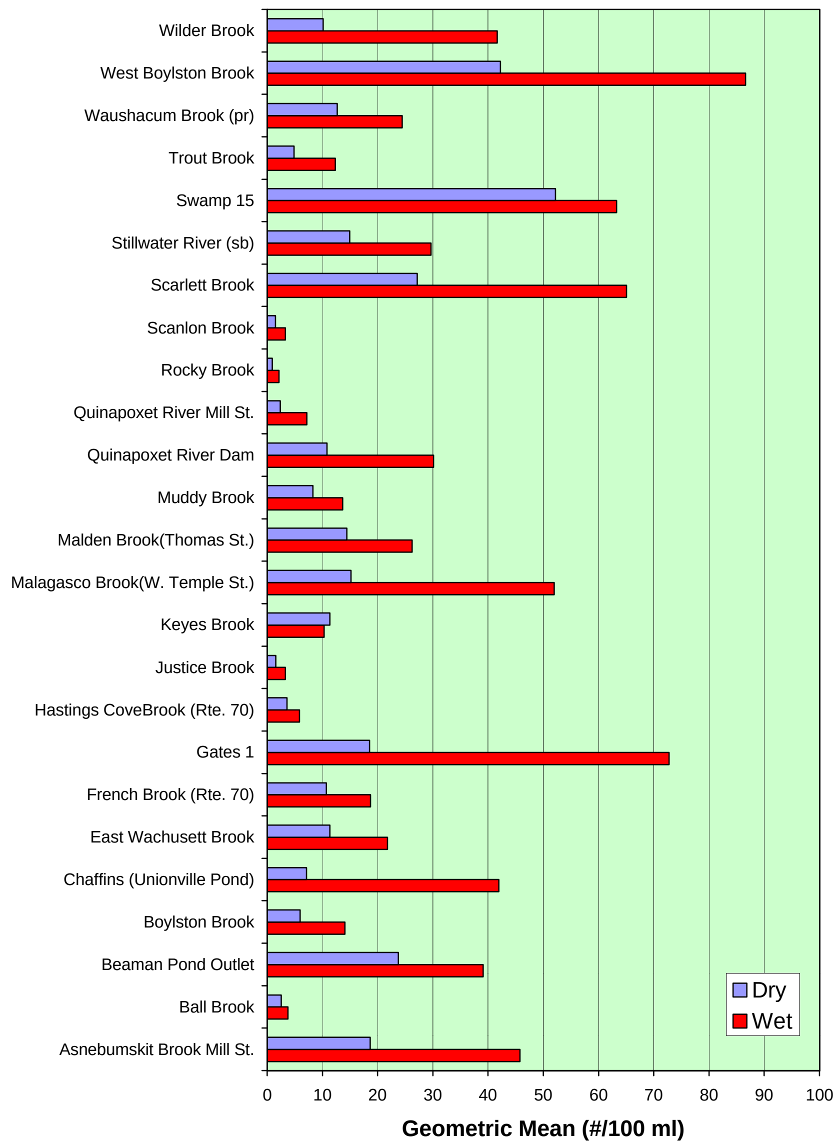
Appendix B

Fecal Coliform Data Analysis

List of Figures

List of Tables

Figure B - 2
Fecal Coliform Counts & Upstream Land Use at Watershed Monitoring Stations
Geometric Means



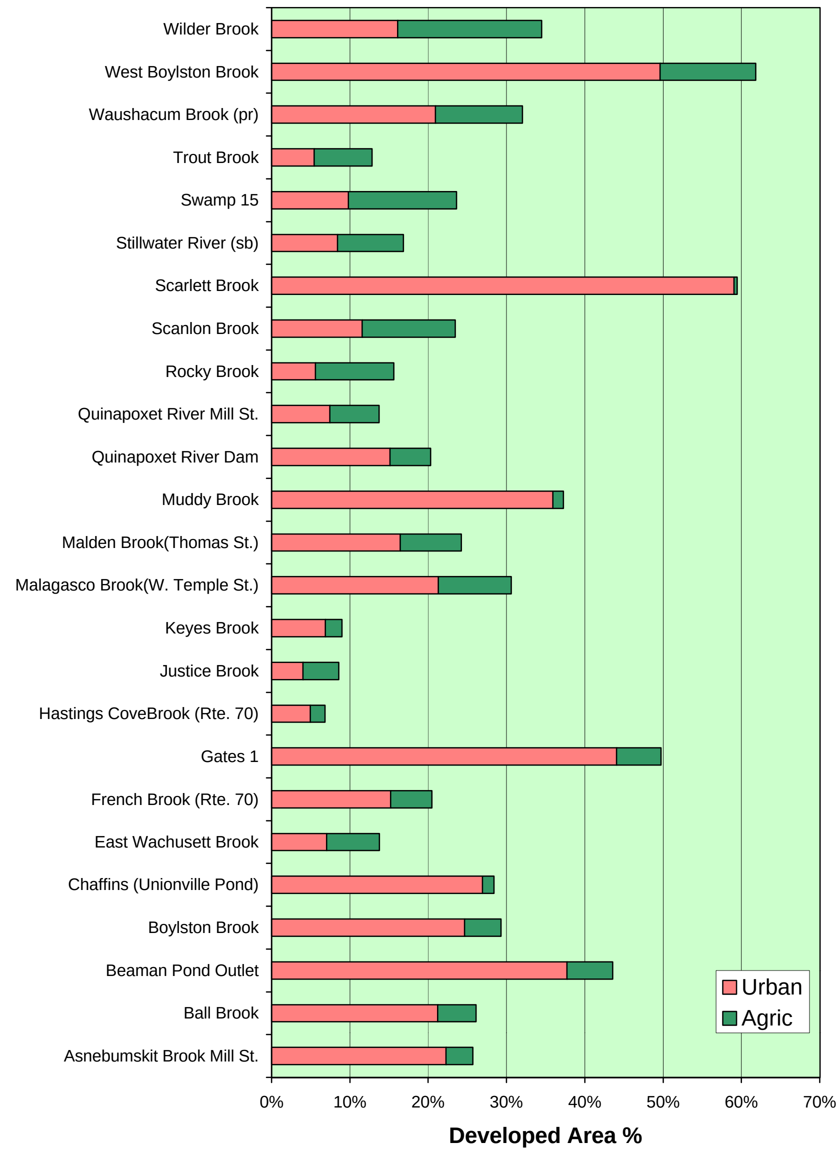
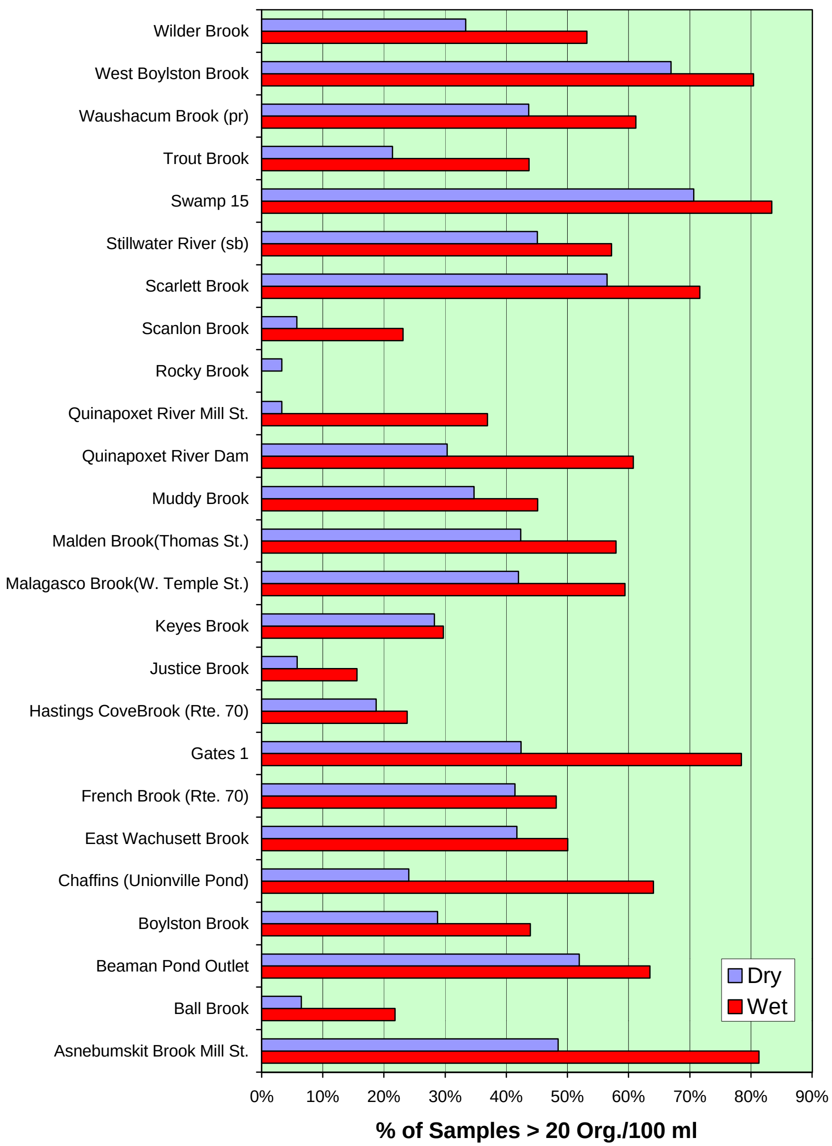


Figure B - 3
Fecal Coliform Counts & Upstream Land Use at Watershed Monitoring Stations
Percent of Samples Exceeding 20 cfu/100 ml Standard



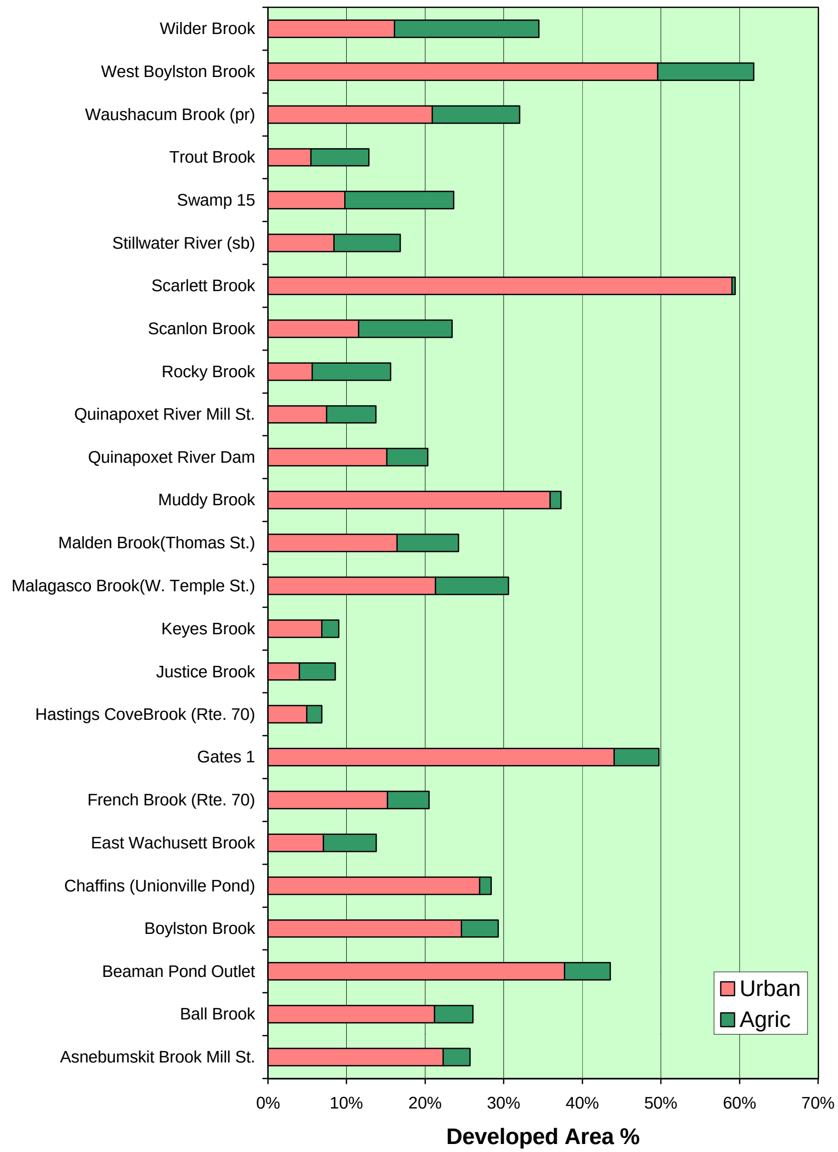
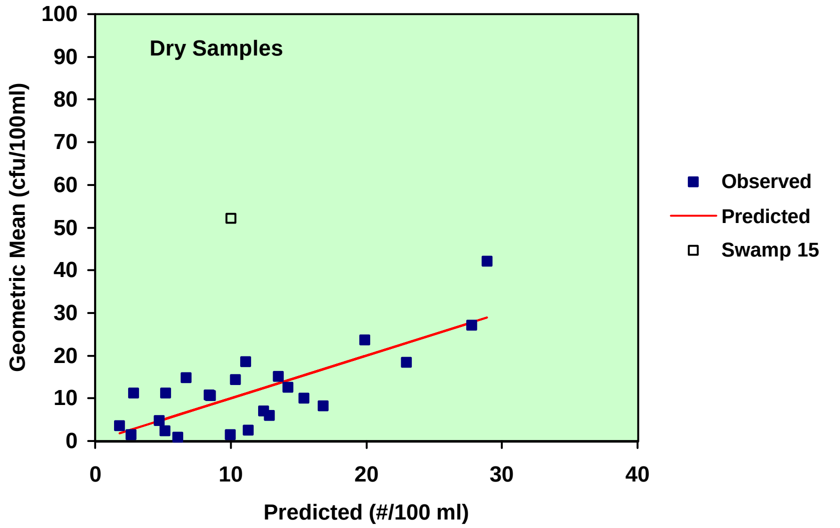


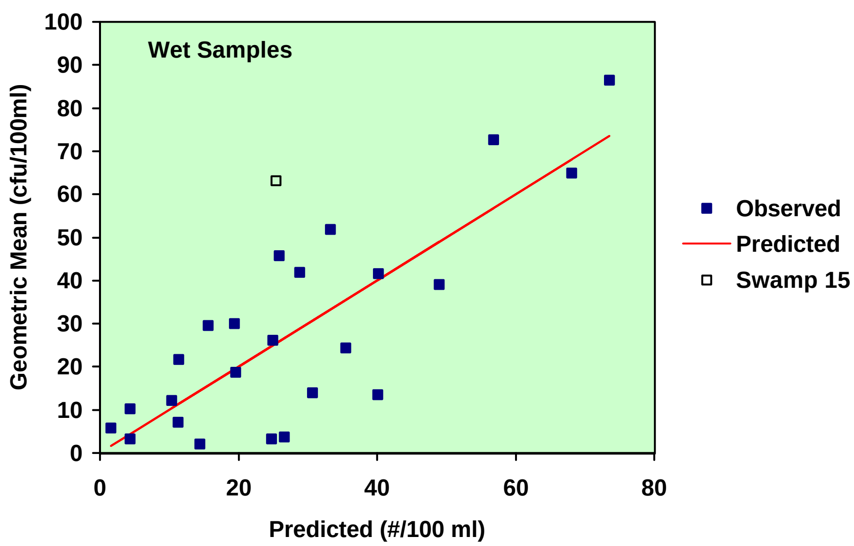
Figure B - 4

Tributary Fecal Coliform Counts Predicted from Land Use Regressions vs. Agricultural & Urban Area



Regression for Dry Samples:

Y =	-1.59	+	49.03 F_{agric}	+	49.41 F_{urban}
R^2 =	0.60		Std Error of Est. =	6.33	



Regression for Wet Samples:

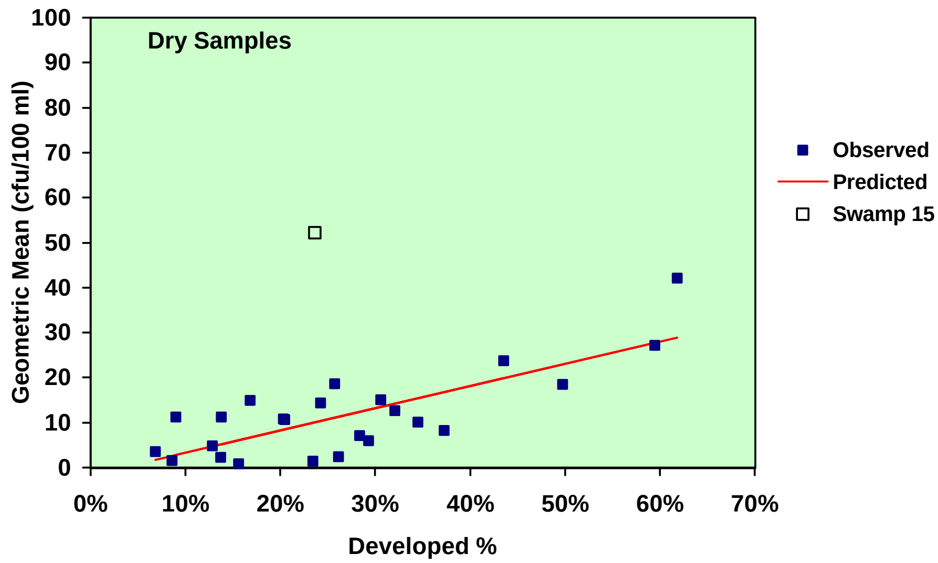
Y =	-7.50	+	148.02 F_{agric}	+	126.90 F_{urban}
R^2 =	0.67		Std Error of Est. =	14.11	

F_{agric} = Fraction Agricultural Land Use

F_{urban} = Fraction Urban Land Use

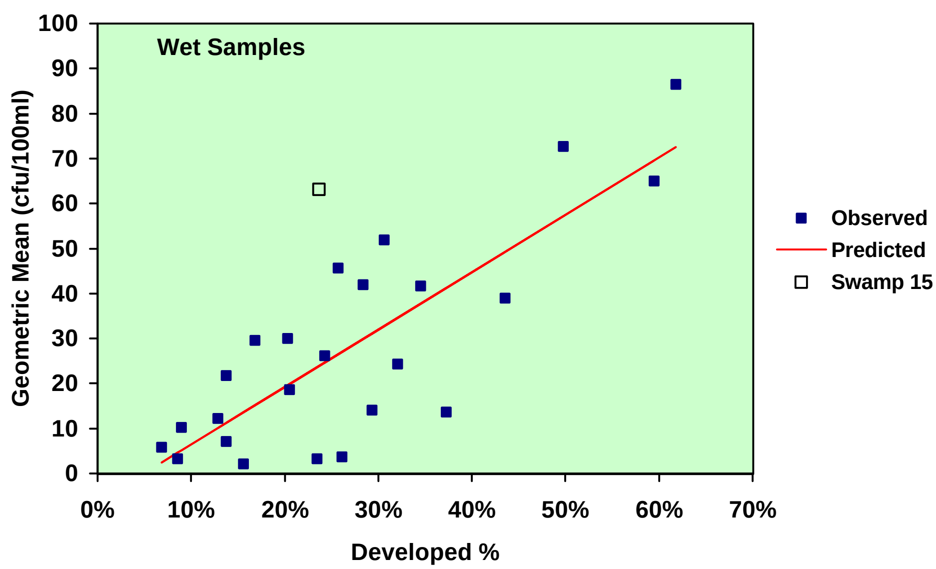
Swamp 15 excluded from regression (limited data)

Figure B - 5
Tributary Fecal Coliform Counts Predicted from Land Use Regressions vs. Developed Area



Regression for Dry Samples:

Y =	-1.61	+	49.40 F_{devel}		
R^2 =	0.60		Std Error of Est. =		6.33



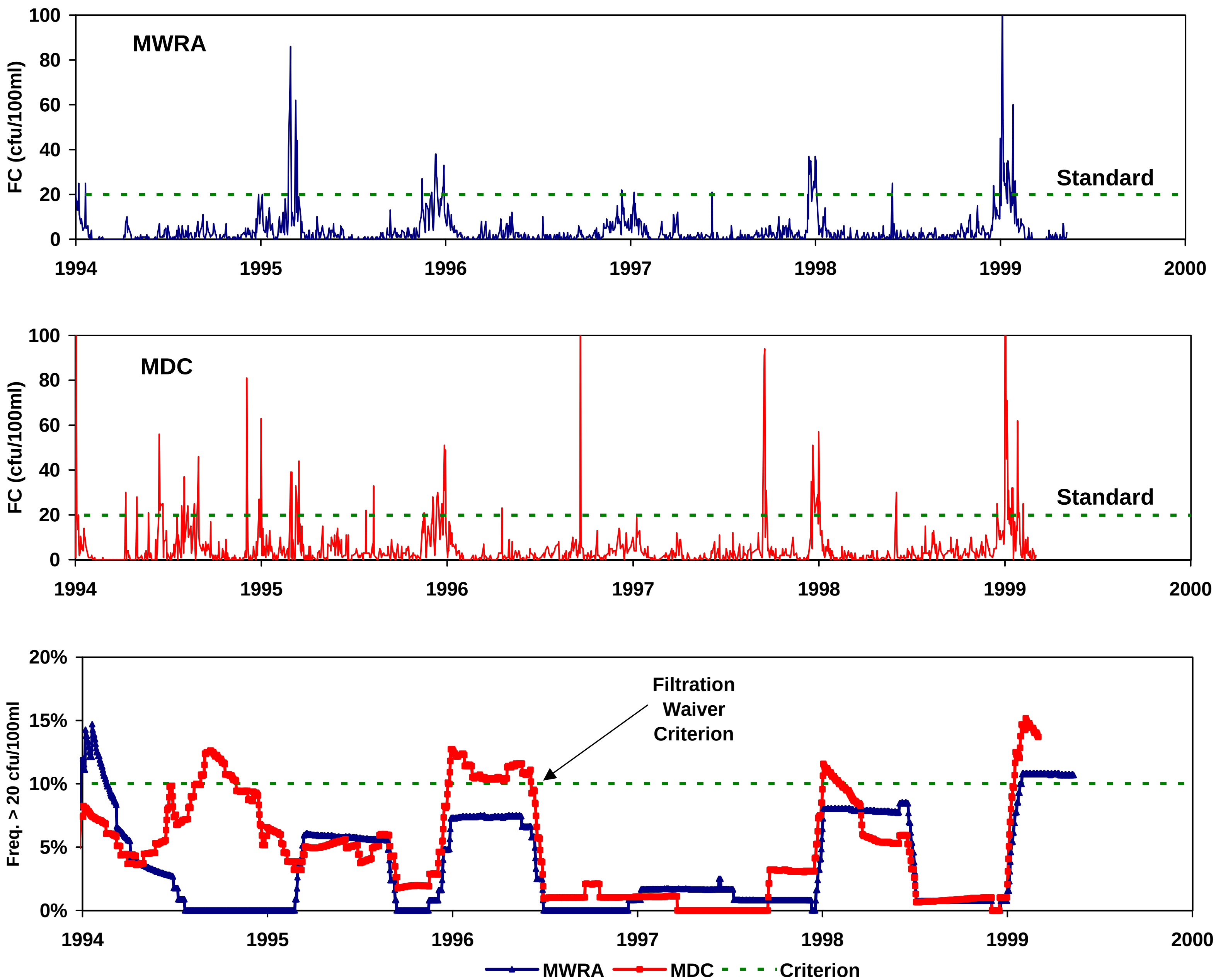
Regression for Wet Samples:

Y =	-6.30	+	127.57 F_{devel}		
R^2 =	0.67		Std Error of Est. =		13.81

F_{devel} = Fraction Agricultural + Urban Land Use
Swamp 15 excluded from regression (limited data)

Figure B - 6

MDC & MWRA Fecal Coliform Data from Cosgrove Intake



Coliform Counts are Daily Values, Exceedence Frequencies are 6-Month Rolling Averages

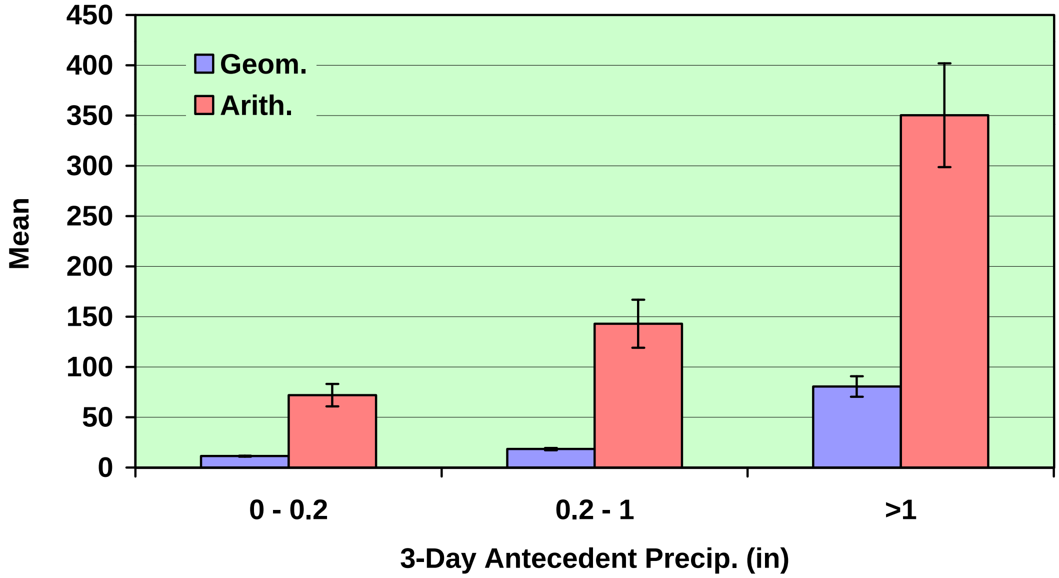
Figure B - 7

Fecal Coliforms vs. Antecedent Precipitation

Geometric & Arithmetic Means

Wachusett Reservoir Watershed & Cosgrove Intake

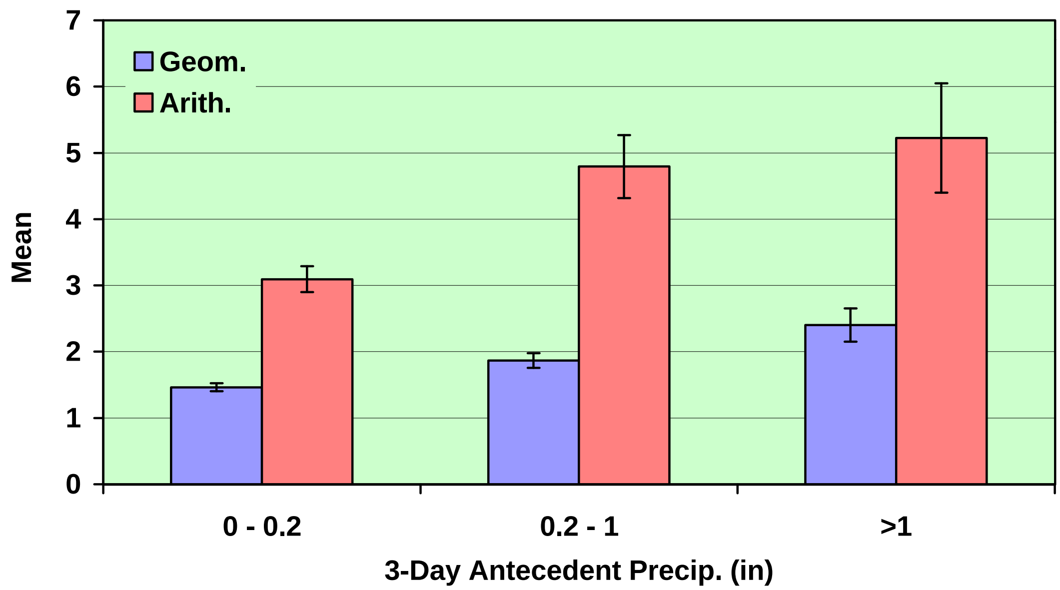
Tributary Stations: **Fecal Coliforms (cfu/100 ml) +/- 1 Std. Error**



Samples:	**1566**	**936**	**239**

Precip. Response Significant at p < 0.001

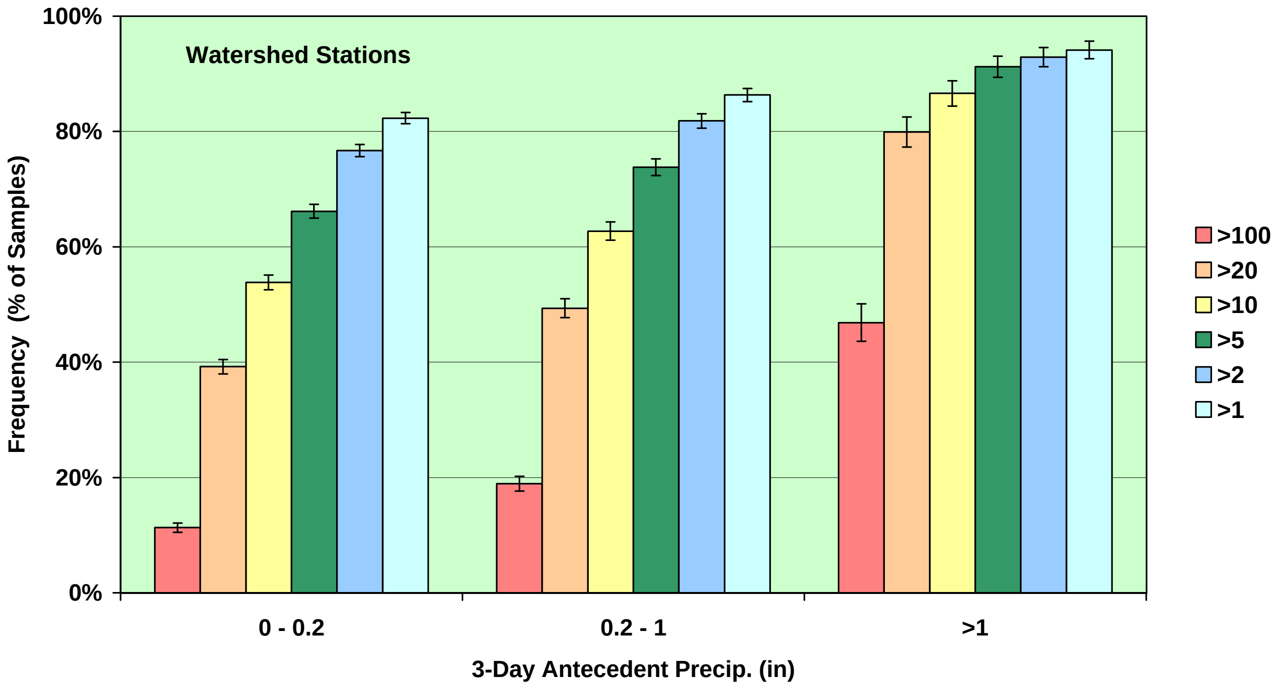
Cosgrove Intake: **Fecal Coliforms (cfu/100 ml) +/- 1 Std. Error**

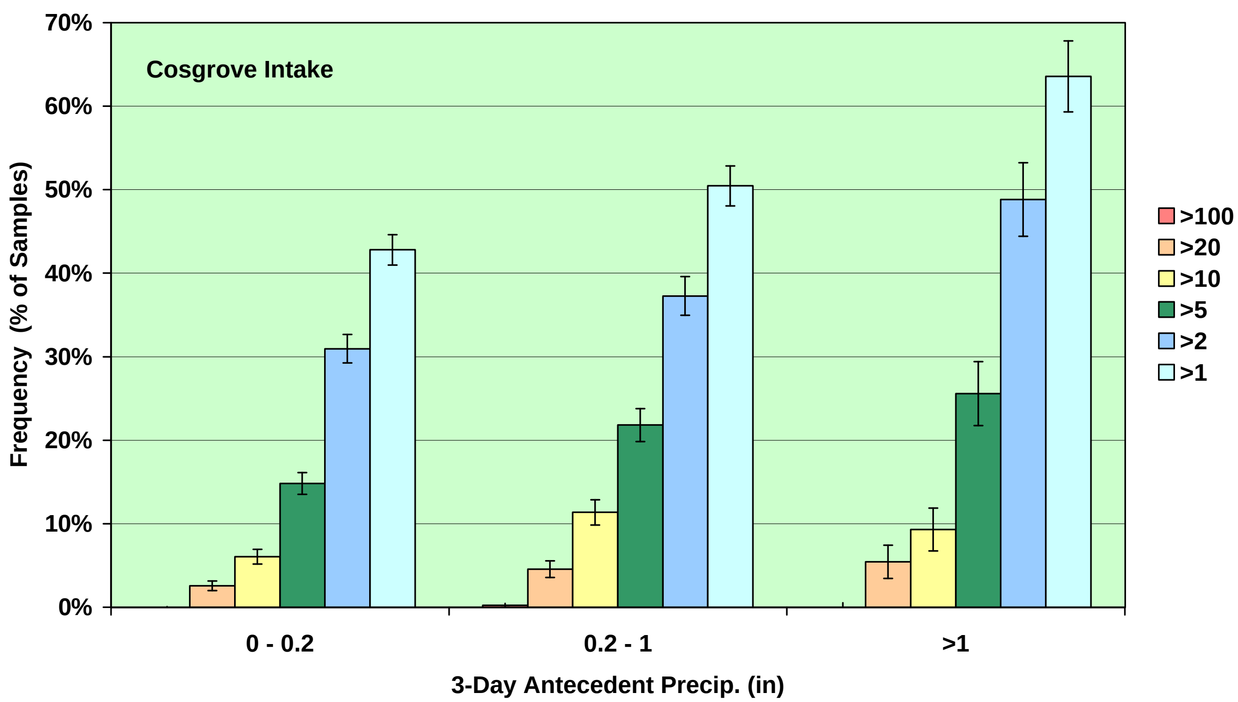


Samples:	**743**	**440**	**129**

Precip. Response Significant at p < 0.001

Figure B - 8
Fecal Coliform Exceedence Frequencies vs. Antecedent Precipitation

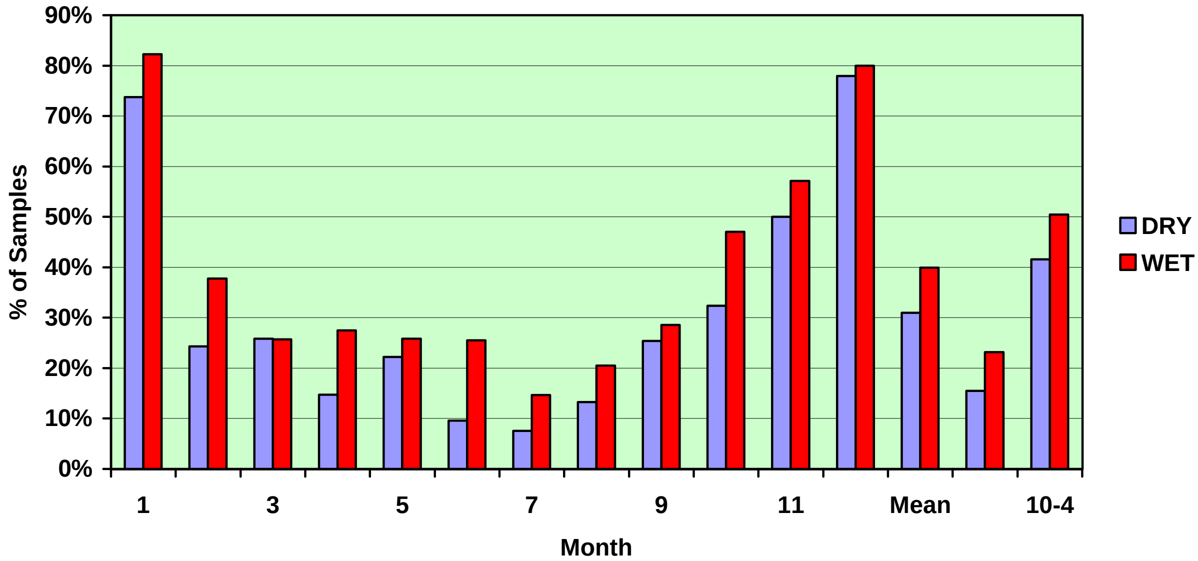




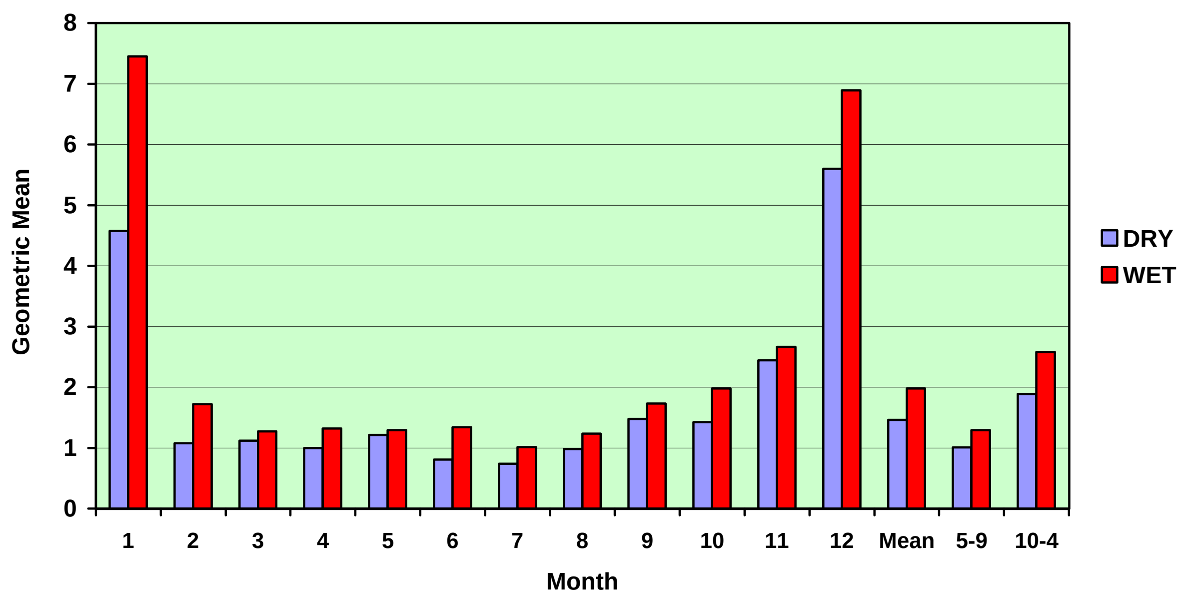
Means +/- 1 Standard Error

Figure B - 9
Seasonal Variations in Fecal Coliform Counts during Dry & Wet Weather
Cosgrove Intake

Frequency > 2 cfu / 100ml



Geometric Mean (cfu / 100 ml)

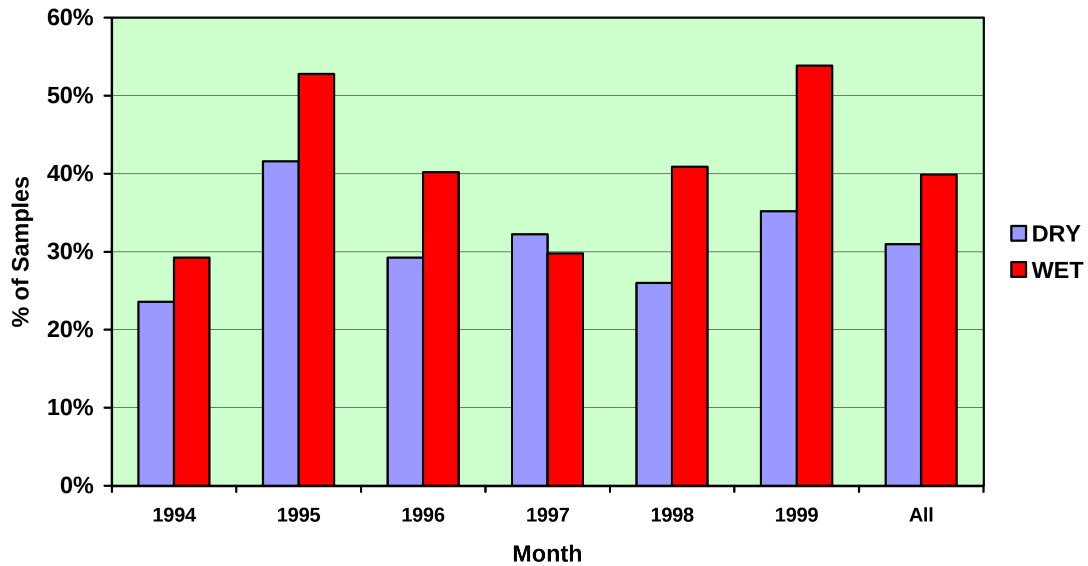


Month & Precipitation Effects Significant at p < .001

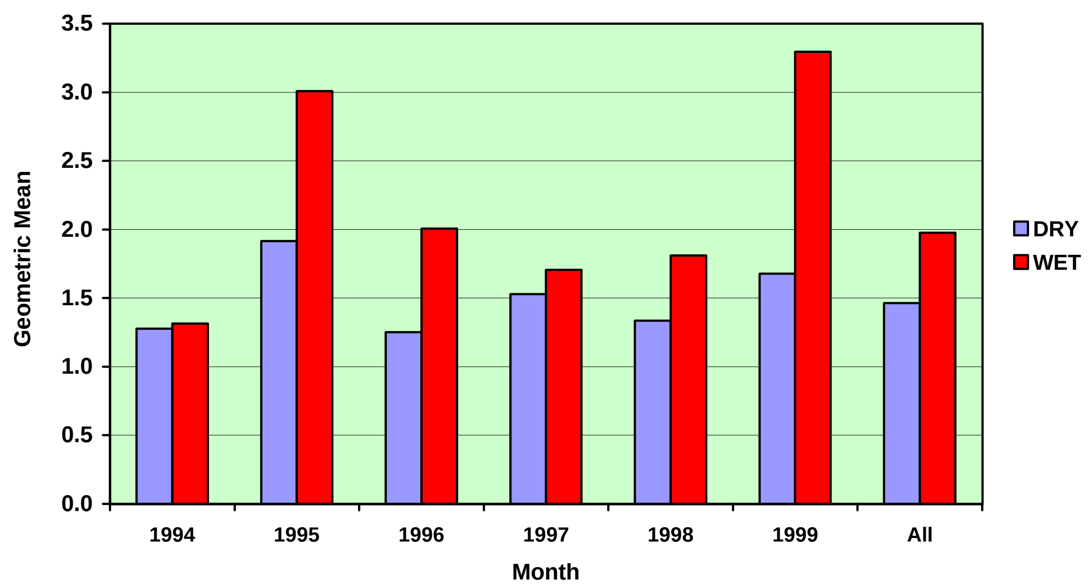
WET:	**3 -Day Antecedent Precip. >=**	**0.2**	**inches**
DRY:	**3 -Day Antecedent Precip. <**	**0.2**	**inches**

Figure B - 10
Yearly Variations in Fecal Coliform Counts during Dry & Wet Weather
Cosgrove Intake

Frequency > 2 cfu / 100ml



Geometric Mean (cfu / 100 ml)



Year & Precipitation Effects Significant at p < .001

WET:	**3 -Day Antecedent Precip. >=**	**0.2**	**inches**
DRY:	**3 -Day Antecedent Precip. <**	**0.2**	**inches**

Table B - 1
Summary of Watershed Fecal Coliform Counts

Units: colonies / 1000 ml

					All Samples --->					Dry Samples --->					Wet Samples --->				
Station	**Type**	**Basin**	**First Date**	**Last Date**	**Count**	**Arith. Mean**	**Geom. Mean**	**CV**	**F > 20**	**Count**	**Arith. Mean**	**Geom. Mean**	**CV**	**F > 20**	**Count**	**Arith. Mean**	**Geom. Mean**	**CV**	**F > 20**
Asnebumskit Brook Mill St.	S	Qu	01/17/95	04/14/99	112	83	27.3	1.42	63%	64	78	18.6	1.45	48%	48	90	45.7	0.52	81%
Asnebumskit Brook Princeton St.	T	Qu	01/06/99	04/22/99	15	203	119.5	1.07	100%	9	269	155.4	1.19	100%	6	104	80.6	0.34	100%
Ball Brook	S	St	01/06/98	04/20/99	54	114	2.9	1.89	13%	31	174	2.5	1.79	6%	23	33	3.7	0.88	22%
Beaman Pond Outlet	P	Re	01/17/95	04/20/99	95	129	29.4	1.81	57%	54	121	23.7	1.84	52%	41	140	39.0	0.77	63%
Boylston Brook	P	Re	01/05/94	04/20/99	213	64	8.8	1.97	36%	115	40	5.9	1.92	29%	98	94	14.0	0.84	44%
Chaffins (Malden St)	T	Qu	03/21/95	04/14/99	53	220	39.6	1.66	74%	28	101	27.5	1.48	68%	25	353	59.6	0.77	80%
Chaffins (Unionville Pond)	S	Qu	03/21/95	04/14/99	50	95	17.2	1.85	44%	25	23	7.1	1.56	24%	25	167	41.9	0.74	64%
Cook Brook	T	Re	01/06/98	04/14/99	48	1085	153.4	2.17	83%	28	499	98.4	2.12	75%	20	1904	285.5	0.93	95%
East Wachusett Brook	S	St	01/17/95	04/20/99	110	299	15.2	2.19	45%	60	206	11.3	2.04	42%	50	409	21.7	1.01	50%
French Brook (Cross St.)	T	Re	01/17/95	12/12/95	43	94	14.9	2.27	47%	21	105	12.3	2.39	43%	22	84	17.9	0.95	50%
French Brook (Linden St.)	T	Re	01/17/95	12/12/95	28	18	3.5	1.75	14%	13	3	1.3	1.15	0%	15	30	8.3	0.77	27%
French Brook (Rte. 70)	P	Re	01/05/94	04/20/99	239	89	13.7	2.11	44%	133	56	10.7	2.03	41%	106	131	18.7	0.95	48%
Gates 1	P	Re	01/05/94	04/14/99	262	247	33.0	1.72	58%	151	67	18.5	1.44	42%	111	491	72.7	0.77	78%
Gates 2	T	Re	01/17/95	04/14/99	212	385	77.1	1.48	84%	125	142	51.2	1.25	78%	87	734	138.7	0.69	94%
Gates 3	T	Re	01/17/95	04/14/99	210	407	69.7	1.50	83%	124	142	45.8	1.20	78%	86	790	127.5	0.73	90%
Gates 4	T	Re	01/17/95	04/14/99	210	365	101.9	1.32	93%	124	184	74.3	1.17	90%	86	625	160.7	0.61	98%
Gates 6	T	Re	01/17/95	04/14/99	212	432	60.9	1.84	69%	124	153	43.3	1.65	64%	88	826	98.4	0.87	77%
Gates 9	T	Re	01/11/96	04/14/99	165	130	26.6	1.74	56%	100	57	19.5	1.59	51%	65	242	43.0	0.81	63%
Hastings CoveBrook (Rte. 70)	P	Re	01/17/95	04/20/99	187	108	4.4	1.96	21%	107	111	3.6	1.89	19%	80	105	5.8	0.88	24%
Justice Brook	S	St	01/17/95	04/20/99	212	9	2.1	1.52	10%	122	5	1.5	1.34	6%	90	15	3.3	0.71	16%
Keyes Brook	S	St	01/06/98	04/20/99	66	33	10.8	1.48	29%	39	26	11.3	1.30	28%	27	44	10.2	0.75	30%
Landfill Brook	T	Qu	01/06/99	04/14/99	15	9	1.4	1.65	13%	9	2	1.0	0.90	0%	6	19	2.4	1.05	33%
Malagasco Brook(W. Temple St.)	P	Re	01/05/94	04/20/99	215	202	25.5	2.12	49%	124	74	15.1	1.95	42%	91	375	51.9	0.93	59%
Malden Brook(Goodale St.)	T	Th	01/17/95	12/12/95	47	117	28.6	1.61	53%	24	66	27.0	1.34	54%	23	170	30.3	0.82	52%
Malden Brook(Lee St.)	T	Th	01/17/95	12/12/95	36	36	10.3	1.87	39%	16	24	5.7	1.91	25%	20	47	16.6	0.75	50%
Malden Brook(Malden St.)	T	Th	01/17/95	12/12/95	43	36	1.7	2.40	21%	23	38	1.8	2.47	22%	20	34	1.6	1.03	20%
Malden Brook(Thomas St.)	P	Th	01/05/94	04/20/99	263	59	18.6	1.61	49%	149	40	14.3	1.51	42%	114	84	26.2	0.73	58%
Muddy Brook	P	Re	01/05/94	04/20/99	215	66	10.2	2.00	39%	124	42	8.2	1.87	35%	91	98	13.6	0.92	45%
Quabbin Aqueduct	P	Aq	01/11/94	12/09/97	96	1	0.6	0.38	0%	61	1	0.6	0.42	0%	35	1	0.6	0.13	0%
Quinapoxet River Dam	P	Qu	01/05/94	04/14/99	264	46	16.7	1.40	43%	152	23	10.8	1.20	30%	112	76	30.1	0.62	61%
Quinapoxet River Mill St.	S	Qu	01/06/98	12/15/98	50	10	3.6	1.52	16%	31	6	2.3	1.40	3%	19	16	7.1	0.65	37%
Rocky Brook	S	St	01/06/98	04/20/99	55	3	1.3	1.16	2%	31	2	0.9	1.01	3%	24	4	2.1	0.51	0%
Scanlon Brook	S	St	01/06/98	04/20/99	61	16	2.1	1.73	13%	35	4	1.5	1.38	6%	26	31	3.3	0.89	23%
Scarlett Brook	S	Re	01/17/95	04/14/99	212	249	39.0	1.71	63%	124	142	27.1	1.51	56%	88	401	65.0	0.81	72%
Stillwater River (62)	T	St	01/17/95	12/12/95	47	111	35.1	1.74	62%	24	100	26.6	1.72	54%	23	123	46.8	0.76	70%
Stillwater River (sb)	P	St	01/11/94	04/20/99	263	101	19.9	1.94	50%	151	57	14.9	1.87	45%	112	159	29.6	0.85	57%
Swamp 15	S	Qu	04/11/95	12/12/95	35	384	57.6	1.63	77%	17	679	52.1	2.05	71%	18	106	63.2	0.51	83%
Trout Brook	S	Qu	01/11/94	04/14/99	160	40	7.3	1.97	31%	89	22	4.8	1.77	21%	71	62	12.3	0.91	44%
Waushacum Brook (f)	T	Th	01/06/98	12/15/98	50	69	27.0	1.52	58%	31	34	18.7	1.28	52%	19	126	49.0	0.75	68%
Waushacum Brook (pr)	P	Th	01/05/94	04/20/99	166	47	16.8	1.57	51%	94	28	12.6	1.49	44%	72	72	24.4	0.70	61%
West Boylston Brook	P	Re	01/05/94	04/14/99	263	299	57.3	1.64	73%	151	244	42.2	1.54	67%	112	372	86.5	0.73	80%
Wilder Brook	S	St	01/17/95	04/20/99	65	567	20.2	2.47	43%	33	107	10.1	2.27	33%	32	1041	41.6	1.08	53%
All Stations			01/05/94	04/22/99	5417	174	18.4	2.09	50%	3090	92	13.1	1.96	44%	2327	284	28.7	0.94	59%
Primary Stations	P		01/05/94	04/20/99	2741	120	15.9	2.00	46%	1566	72	11.3	1.87	39%	1175	185	24.8	0.90	56%
Secondary Stations	S		01/11/94	04/20/99	1242	136	9.1	2.11	36%	701	86	6.2	1.97	28%	541	200	14.7	0.95	45%
Tertiary Stations	T		01/17/95	04/22/99	1434	310	44.9	1.93	71%	823	134	33.0	1.76	66%	611	548	68.2	0.90	77%

Table B - 2
Fecal Coliform Counts & Upstream Land Use at Watershed Monitoring Stations

Station	Type	Sub-Wtrshd	Cum. Area acres	Cumulative Land Use Urban%	Agric%	Dev%	Sampl Count	All Samples-----> Arith. Mean	Geom. Mean	F > 20	Dry Samples-----> Arith. Mean	Geom. Mean	F > 20	Wet Samples----> Arith. Mean	Geom. Mean	F > 20
Asnebumskit Brook Mill St.	S	32	2827	22%	3%	26%	112	83.3	27.3	63%	78.4	18.6	48%	89.8	45.7	81%
Ball Brook	S	11	481	21%	5%	26%	54	114.2	2.9	13%	174.3	2.5	6%	33.2	3.7	22%
Beaman Pond Outlet	P	26	373	38%	6%	44%	95	129.4	29.4	57%	121.3	23.7	52%	140.0	39.0	63%
Boylston Brook	P	41	140	25%	5%	29%	213	64.5	8.8	36%	39.5	5.9	29%	93.7	14.0	44%
Chaffins (Unionville Pond)	S	39	4094	27%	1%	28%	50	95.4	17.2	44%	23.4	7.1	24%	167.4	41.9	64%
East Wachusett Brook	S	4	5706	7%	7%	14%	110	298.7	15.2	45%	206.4	11.3	42%	409.4	21.7	50%
French Brook (Rte. 70)	P	33	1375	15%	5%	20%	239	89.2	13.7	44%	55.6	10.7	41%	131.4	18.7	48%
Gates 1	P	38	1964	44%	6%	50%	262	246.5	33.0	58%	67.0	18.5	42%	490.7	72.7	78%
Hastings CoveBrook (Rte. 70)	P	31	389	5%	2%	7%	187	108.4	4.4	21%	111.2	3.6	19%	104.5	5.8	24%
Justice Brook	S	3	3182	4%	5%	9%	212	9.3	2.1	10%	5.1	1.5	6%	15.1	3.3	16%
Keyes Brook	S	2	3206	7%	2%	9%	66	33.4	10.8	29%	26.4	11.3	28%	43.6	10.2	30%
Malagasco Brook(W. Temple	P	44	562	21%	9%	31%	215	201.5	25.5	49%	73.9	15.1	42%	375.5	51.9	59%
Malden Brook(Thomas St.)	P	29	1216	16%	8%	24%	263	59.1	18.6	49%	40.2	14.3	42%	83.8	26.2	58%
Muddy Brook	P	45	534	36%	1%	37%	215	65.6	10.2	39%	42.1	8.2	35%	97.6	13.6	45%
Quinapoxet River Dam	P	21	17300	15%	5%	20%	264	45.7	16.7	43%	23.1	10.8	30%	76.3	30.1	61%
Quinapoxet River Mill St.	S	22	1564	7%	6%	14%	50	9.8	3.6	16%	5.8	2.3	3%	16.4	7.1	37%
Rocky Brook	S	5	1950	6%	10%	16%	55	2.8	1.3	2%	2.2	0.9	3%	3.7	2.1	0%
Scanlon Brook	S	13	829	12%	12%	23%	61	15.5	2.1	13%	4.3	1.5	6%	30.7	3.3	23%
Scarlett Brook	S	42	320	59%	0%	59%	212	249.3	39.0	63%	141.6	27.1	56%	401.2	65.0	72%
Stillwater River (sb)	P	10	19430	8%	8%	17%	263	100.9	19.9	50%	57.5	14.9	45%	159.4	29.6	57%
Swamp 15	S	37	698	10%	14%	24%	35	384.2	57.6	77%	679.1	52.1	71%	105.7	63.2	83%
Trout Brook	S	12	4430	5%	7%	13%	160	39.7	7.3	31%	22.3	4.8	21%	61.5	12.3	44%
Waushacum Brook (pr)	P	15	4090	21%	11%	32%	166	47.1	16.8	51%	27.7	12.6	44%	72.5	24.4	61%
West Boylston Brook	P	35	260	50%	12%	62%	263	298.6	57.3	73%	244.4	42.2	67%	371.7	86.5	80%
Wilder Brook	S	9	830	16%	18%	34%	65	566.6	20.2	43%	106.7	10.1	33%	1041.0	41.6	53%
Quabbin Aquaduct **	I		55968				96	0.6	0.6	0.0%	0.7	0.6	0.0%	0.6	0.6	0.0%
Cosgrove Intake	O		53030	15%	7%	22%	1312	3.9	1.7	3.5%	4.9	2.0	4.7%	3.1	1.5	2.6%
Area-Weighted Means*:																
Primary Stations	P		47633	15%	7%	22%	251.1	82.9	18.9	48%	44.3	13.2	39%	134.9	30.9	59%
Secondary Stations	S		30117	12%	6%	18%	104.7	117.9	12.9	34%	79.8	9.0	26%	161.9	21.3	44%
Watershed + Quabbin Aqued. Total			108998				171.5	40.6	9.5	23%	21.9	6.7	19%	65.9	15.3	29%

Monitoring Data from 1994-1999   Wet Samples have >0.2 inches of precipitation in 3 days prior to sampling event..

Cumulative Watershed Area = Total area within & upstream of subwatershed where station is located, excluding Worcester water-supply subwatersheds.

F > 20 = Frequency of Coliform Samples Exceeding Drinking Water Criterion (20 org/100 ml)

P = Primary Stations (direct inflows to Wachusett Reservoir)   S = Secondary Stations (tributary subwatersheds)

Total watershed area (excluding Worcester subwatersheds & reservoir surface) = 53030 acres

Primary stations represent 47633 out of 53030 acres or 90% of watershed

Estimate of average inflow concentration to Wachusett Reservoir * = 83 org / 100ml from watershed or 41 org. / 100ml from watershed + quabbin

*Area-weighted means estimate flow-weighted means across watersheds, assuming that unit area flows are uniform across watersheds. Since concentration is likely to increase with flow at some watershed stations, the weighting procedure is likely to under-estimate average inflow concentrations to the reservoir from the watershed.

**Total inflow to Wachusett Reservoir from local watershed & Quabbin estimated from area-weighted-means of Primary stations & Quabbin. To account for unsampled regions, a total area of 53,030 acres is assigned to the primary stations . To provide an approximate flow-weighting, the effective drainage area of Quabbin diversions is estimated at 1.175 x 53,030 or 55,968 acres, where 1.175 = 235 cfs / 200 cfs = ratio of Quabbin inflows to watershed inflows indicated in 1998 watershed management plan (Table 2-6).

Table B - 3
Cumulative Land Uses by Subwatershed

			Subwatershed Areas (acres)				Cumulative Areas (acres) *				Cumulative Percents		
No.	Name	District	Total	Undev	Agric	Urban	Total	Undev	Agric	Urban	Undev	Agric	Urban
2	KEYES BROOK	STILLWATER	3205.9	2917.8	68.1	219.9	3205.9	2917.8	68.1	219.9	91.0%	2.1%	6.9%
3	JUSTICE BROOK	STILLWATER	3182.0	2909.2	145.8	127.0	3182.0	2909.2	145.8	127.0	91.4%	4.6%	4.0%
4	EAST WACHUSETT BROOK	STILLWATER	5705.6	4920.9	382.8	401.9	5705.6	4920.9	382.8	401.9	86.2%	6.7%	7.0%
5	ROCKY BROOK	STILLWATER	1950.0	1645.7	195.1	109.3	1950.0	1645.7	195.1	109.3	84.4%	10.0%	5.6%
6	DAVIS FARM/US FARM	STILLWATER	1129.6	993.9	81.8	53.8	7517.6	6821.0	295.7	400.8	90.7%	3.9%	5.3%
7	WORC/QUIN	WORCESTER	12606.0	10854.1	1095.2	656.7	12606.0	10854.1	1095.2	656.7	86.1%	8.7%	5.2%
8	UPPER WAUSHACUM BROO	THOMAS BASII	2400.5	1669.6	262.5	468.3	2400.5	1669.6	262.5	468.3	69.6%	10.9%	19.5%
9	WILDER BROOK	STILLWATER	830.1	543.8	152.8	133.5	830.1	543.8	152.8	133.5	65.5%	18.4%	16.1%
10	STILLWATER @ STEEL BRID	STILLWATER	1454.4	848.5	309.3	296.5	19430.2	16161.7	1633.9	1634.6	83.2%	8.4%	8.4%
11	BALL BROOK	STILLWATER	481.4	355.8	23.6	102.0	481.4	355.8	23.6	102.0	73.9%	4.9%	21.2%
12	TROUT BROOK	QUINAPOXET	4430.2	3862.1	327.1	241.1	4430.2	3862.1	327.1	241.1	87.2%	7.4%	5.4%
13	SCANLON BROOK	STILLWATER	829.3	634.9	98.6	95.8	829.3	634.9	98.6	95.8	76.6%	11.9%	11.5%
14	HOUGHTON BROOK	STILLWATER	661.9	391.2	176.0	94.7	661.9	391.2	176.0	94.7	59.1%	26.6%	14.3%
15	LOWER WAUSHACUM BROC	THOMAS BASII	1689.9	1110.3	192.3	387.4	4090.4	2779.9	454.8	855.7	68.0%	11.1%	20.9%
16	HOG HILL	QUINAPOXET	947.5	816.7	80.6	50.3	947.5	816.7	80.6	50.3	86.2%	8.5%	5.3%
17	THOMAS BASIN/SHORELINE	THOMAS BASII	1070.3	883.2	101.2	85.8	43604.1	34808.8	3225.6	5569.7	79.8%	7.4%	12.8%
18	GATE 36 TO 42	RESERVOIR	68.6	43.0	17.5	8.1	68.6	43.0	17.5	8.1	62.7%	25.5%	11.8%
19	WACHUSETT R	RESERVOIR	3818.6	3817.3	0.0	1.2	56846.3	45626.2	3682.7	7537.4	80.3%	6.5%	13.3%
20	GATE 26 TO 35	RESERVOIR	1456.3	1334.1	63.9	58.3	1456.3	1334.1	63.9	58.3	91.6%	4.4%	4.0%
21	LOWER QUINAPOXET	QUINAPOXET	1612.1	1416.6	66.1	129.4	17299.6	13784.2	901.9	2613.6	79.7%	5.2%	15.1%
22	UPPER QUINAPOXET	QUINAPOXET	1564.0	1349.4	98.2	116.4	1564.0	1349.4	98.2	116.4	86.3%	6.3%	7.4%
23	OAKDALE	THOMAS BASII	330.2	188.8	36.1	105.4	330.2	188.8	36.1	105.4	57.2%	10.9%	31.9%
24	GATE 1 TO 5	RESERVOIR	437.4	411.7	2.9	22.8	437.4	411.7	2.9	22.8	94.1%	0.7%	5.2%
25	MIDDLE QUINAPOXET	QUINAPOXET	1126.9	774.4	76.5	276.1	10309.8	7688.8	428.2	2192.7	74.6%	4.2%	21.3%
26	BEAMAN POND	THOMAS BASII	372.7	210.4	21.7	140.6	372.7	210.4	21.7	140.6	56.5%	5.8%	37.7%
27	WORC/PINEHILL/KENDALL	WORCESTER	5438.2	4286.9	616.1	535.2	5438.2	4286.9	616.1	535.2	78.8%	11.3%	9.8%
28	GATE 6 TO 16	RESERVOIR	823.9	752.5	40.9	30.5	823.9	752.5	40.9	30.5	91.3%	5.0%	3.7%
29	MALDEN BROOK	THOMAS BASII	1216.0	921.3	95.2	199.6	1216.0	921.3	95.2	199.6	75.8%	7.8%	16.4%
30	CRESCENT	THOMAS BASII	167.3	89.6	2.5	75.1	167.3	89.6	2.5	75.1	53.6%	1.5%	44.9%
31	HASTINGS COVE BROOK	RESERVOIR	388.7	362.1	7.4	19.2	388.7	362.1	7.4	19.2	93.2%	1.9%	4.9%
32	ASNEBUMSKIT BROOK	QUINAPOXET	1519.8	885.4	82.5	551.9	2826.8	2099.9	96.8	630.1	74.3%	3.4%	22.3%
33	FRENCH BROOK	RESERVOIR	1374.6	1093.1	72.8	208.7	1374.6	1093.1	72.8	208.7	79.5%	5.3%	15.2%
34	GATE 17 TO 25	RESERVOIR	609.5	575.7	3.7	30.0	609.5	575.7	3.7	30.0	94.5%	0.6%	4.9%
35	WEST BOYLSTON BROOK	RESERVOIR	259.6	99.1	31.8	128.8	259.6	99.1	31.8	128.8	38.2%	12.2%	49.6%
36	EAGLE LAKE	QUINAPOXET	1307.0	1214.5	14.4	78.2	1307.0	1214.5	14.4	78.2	92.9%	1.1%	6.0%
37	SWAMP 15	QUINAPOXET	698.5	533.4	96.7	68.4	698.5	533.4	96.7	68.4	76.4%	13.8%	9.8%
38	GATES BROOK	RESERVOIR	1644.7	857.6	110.8	676.3	1964.4	987.2	112.1	865.1	50.3%	5.7%	44.0%
39	LOWER CHAFFIN/UNIONVILI	QUINAPOXET	1577.9	981.5	19.4	577.1	4093.5	2931.8	60.0	1101.8	71.6%	1.5%	26.9%
40	PINE HILL	RESERVOIR	130.0	84.9	7.3	37.8	130.0	84.9	7.3	37.8	65.3%	5.6%	29.1%
41	BOYLSTON BROOK	RESERVOIR	140.2	99.1	6.5	34.5	140.2	99.1	6.5	34.5	70.7%	4.7%	24.6%
42	SCARLETT BROOK	RESERVOIR	319.8	129.6	1.3	188.8	319.8	129.6	1.3	188.8	40.5%	0.4%	59.0%
43	POTASH BROOK	RESERVOIR	120.1	80.0	0.3	39.7	120.1	80.0	0.3	39.7	66.7%	0.3%	33.1%
44	MALAGASCO BROOK	RESERVOIR	562.3	390.2	52.2	119.8	562.3	390.2	52.2	119.8	69.4%	9.3%	21.3%
45	MUDDY BROOK	RESERVOIR	533.7	334.8	7.3	191.6	533.7	334.8	7.3	191.6	62.7%	1.4%	35.9%
46	DIAMOND HILL	RESERVOIR	181.7	142.0	8.6	31.1	181.7	142.0	8.6	31.1	78.2%	4.7%	17.1%
47	CHAFFIN POND	QUINAPOXET	2515.6	1950.2	40.6	524.7	2515.6	1950.2	40.6	524.7	77.5%	1.6%	20.9%

* Cumulative Area = Total area within & upstream of subwatershed, excluding Worcester water-supply subwatersheds.

Table B - 4
Summary of Cosgrove Intake Fecal Coliform Measurements

Data Set	Agency	Location	Sample Dates	Arithmetic Mean	Std Dev	Geometric Mean	CV	Exceedence Frequencies (%) >0	>2	>5	>10	>20
1	MDC	INSIDE	164	4.4	10.2	1.8	1.24	64.0%	39.0%	22.0%	8.5%	1.8%
2	MDC	OUTSIDE	1068	5.6	12.3	2.2	1.26	75.5%	43.6%	24.0%	13.1%	6.2%
3	MWRA	INSIDE	1306	3.9	7.7	1.7	1.19	65.8%	34.8%	18.1%	8.0%	3.5%
4	MWRA	OUTSIDE	146	6.3	11.1	2.6	1.32	76.7%	50.7%	32.2%	19.9%	4.8%
5	MEAN	ALL	1474	4.6	9.2	1.9	1.21	71.4%	41.5%	20.4%	10.7%	4.5%
6	MDC	IN/OUT	1192	5.5	12.2	2.2	1.27	74.1%	43.3%	23.8%	12.5%	5.7%
7 *	MWRA	IN/OUT	1312	3.9	7.7	1.7	1.19	66.0%	34.8%	18.2%	8.2%	3.5%
8	MWRA/MDC	INSIDE	1329	4.0	8.1	1.7	1.19	66.2%	35.2%	18.5%	8.3%	3.6%
9	MWRA/MDC	OUTSIDE	1079	5.7	12.6	2.2	1.27	75.5%	43.7%	24.6%	13.6%	6.0%

Sample Locations

INSIDE	from tap inside pump station
OUTSIDE	from surface of Reservoir in vicinity of intake

Sample Date Ranges

MDC	01/01/94	to	03/02/99
MWRA	01/01/94	to	05/11/99

Data Set

5 arithmetic mean of all measurements collected on a given date
6 MDC samples, using outside samples only on days when inside samples were not available (1028 out of 1192 days)
7 MWRA samples, using outside samples only on days when inside samples were not available (6 out of 1312 days)
8 Inside samples only, using MDC samples only on days when MWRA samples were not available
9 Outside samples only, using MDC samples only on days when MDC samples were not available

Units: Fecal Coliforms cfu/ 100 ml

* Primary data set analyzed in Appendix B

Table B - 5
Fecal Coliforms vs. Antecedent Precipitation at Watershed Stations & Cosgrove Intake

Primary & Secondary Watershed Monitoring Stations, 1994-1999 (Figure B-1)

3-Day Antec. Precip (in)			Log-10 Mean		Arithmetic Mean		Frequency > 2		Frequency > 20		Geometric Mean	
Low	High	Count	Mean	Std_Dev	Mean	SE	Mean	SE	Mean	SE	Mean	SE
0	0.2	1566	1.05	0.81	71.9	11.1	76.7%	1.1%	39.2%	1.2%	11.3	0.5
0.2	1	936	1.26	0.87	143.0	23.9	81.8%	1.3%	49.4%	1.6%	18.4	1.2
1	999	239	1.91	0.85	350.2	51.6	92.9%	1.7%	79.9%	2.6%	80.7	10.2
ALL		2741	1.20	0.87	120.5	11.4	79.9%	0.8%	46.2%	1.0%	15.9	0.6

One-Way Analysis of Variance   Log10 Fecal Coliform Count (# / 100 ml)

	SS	DOF	MS	F	Prob (>F)
Total	2069	2740	0.75		
Precip.	157	2	78.33	112.2	0.000
Residual	1912	2738	0.70		

MWRA Cosgrove Intake Data, 1994-1999

3-Day Antec. Precip (in)			Log-10 Mean		Arithmetic Mean		Frequency > 2		Frequency > 20		Geometric Mean	
Low	High	Count	Mean	Std_Dev	Mean	SE	Mean	SE	Mean	SE	Mean	SE
0	0.2	743	0.17	0.48	3.1	0.2	31.0%	1.7%	2.6%	0.6%	1.5	0.1
0.2	1	440	0.27	0.55	4.8	0.5	37.3%	2.3%	4.5%	1.0%	1.9	0.1
1	999	129	0.38	0.51	5.2	0.8	48.8%	4.4%	5.4%	2.0%	2.4	0.3
ALL		1312	0.22	0.51	3.9	0.2	34.8%	1.3%	3.5%	0.5%	1.7	0.1

One-Way Analysis of Variance   Log10 Fecal Coliform Count (# / 100 ml)

	SS	DOF	MS	F	Prob(>F)
Total	347.2	1311	0.26		
Precip.	6.7	2	3.35	12.90	0.000
Residual	340.5	1309	0.26		

SE = Standard Error of Mean

Table B - 6
Cosgrove Intake Fecal Coliforms vs. Month & Antecedent Precipitation

			Log-10 Mean		Arithmetic Mean		uency > 2		Frequency > 20		Geometric Mean	
Month	Precip	Count	Mean	Std_Dev	Mean	SE	Mean	SE	Mean	SE	Mean	SE
1	DRY	61	0.66	0.48	7.7	1.0	73.8%	5.6%	11.5%	4.1%	4.6	0.6
2	DRY	70	0.03	0.43	1.9	0.3	24.3%	5.1%	0.0%	1.0%	1.1	0.1
3	DRY	58	0.05	0.50	2.8	0.8	25.9%	5.7%	1.7%	1.7%	1.1	0.2
4	DRY	68	0.00	0.33	1.4	0.2	14.7%	4.3%	0.0%	1.0%	1.0	0.1
5	DRY	54	0.08	0.33	1.6	0.2	22.2%	5.7%	0.0%	1.3%	1.2	0.1
6	DRY	52	-0.09	0.33	1.4	0.4	9.6%	4.1%	1.9%	1.9%	0.8	0.1
7	DRY	66	-0.13	0.29	1.0	0.1	7.6%	3.3%	0.0%	1.1%	0.7	0.1
8	DRY	68	-0.01	0.32	1.3	0.2	13.2%	4.1%	0.0%	1.0%	1.0	0.1
9	DRY	63	0.17	0.39	2.3	0.3	25.4%	5.5%	0.0%	1.1%	1.5	0.2
10	DRY	68	0.15	0.37	2.0	0.2	32.4%	5.7%	0.0%	1.0%	1.4	0.1
11	DRY	56	0.39	0.48	4.2	0.6	50.0%	6.7%	0.0%	1.3%	2.4	0.4
12	DRY	59	0.75	0.54	10.2	1.4	78.0%	5.4%	16.9%	4.9%	5.6	0.9
1	WET	62	0.87	0.47	13.1	2.2	82.3%	4.9%	16.1%	4.7%	7.5	1.0
2	WET	45	0.24	0.63	6.8	2.5	37.8%	7.2%	6.7%	3.7%	1.7	0.4
3	WET	70	0.10	0.57	4.1	1.2	25.7%	5.2%	4.3%	2.4%	1.3	0.2
4	WET	51	0.12	0.47	2.5	0.4	27.5%	6.2%	0.0%	1.4%	1.3	0.2
5	WET	58	0.11	0.40	2.1	0.3	25.9%	5.7%	0.0%	1.2%	1.3	0.2
6	WET	47	0.13	0.42	2.4	0.6	25.5%	6.4%	2.1%	2.1%	1.3	0.2
7	WET	41	0.00	0.38	1.6	0.3	14.6%	5.5%	0.0%	1.7%	1.0	0.1
8	WET	39	0.09	0.33	1.6	0.2	20.5%	6.5%	0.0%	1.8%	1.2	0.2
9	WET	35	0.24	0.30	2.2	0.3	28.6%	7.6%	0.0%	2.0%	1.7	0.2
10	WET	34	0.30	0.40	2.8	0.4	47.1%	8.6%	0.0%	2.1%	2.0	0.3
11	WET	42	0.43	0.43	4.3	0.7	57.1%	7.6%	2.4%	2.4%	2.7	0.4
12	WET	45	0.84	0.54	11.9	1.6	80.0%	6.0%	20.0%	6.0%	6.9	1.3
1	ALL	123	0.77	0.49	10.5	1.2	78.0%	3.7%	13.8%	3.1%	5.9	0.6
2	ALL	115	0.11	0.53	3.8	1.0	29.6%	4.3%	2.6%	1.5%	1.3	0.1
3	ALL	128	0.08	0.53	3.5	0.8	25.8%	3.9%	3.1%	1.5%	1.2	0.1
4	ALL	119	0.05	0.40	1.8	0.2	20.2%	3.7%	0.0%	0.6%	1.1	0.1
5	ALL	112	0.10	0.37	1.9	0.2	24.1%	4.0%	0.0%	0.6%	1.3	0.1
6	ALL	99	0.01	0.39	1.8	0.3	17.2%	3.8%	2.0%	1.4%	1.0	0.1
7	ALL	107	-0.08	0.33	1.2	0.1	10.3%	2.9%	0.0%	0.7%	0.8	0.1
8	ALL	107	0.03	0.32	1.4	0.1	15.9%	3.5%	0.0%	0.7%	1.1	0.1
9	ALL	98	0.19	0.36	2.2	0.2	26.5%	4.5%	0.0%	0.7%	1.6	0.1
10	ALL	102	0.20	0.38	2.3	0.2	37.3%	4.8%	0.0%	0.7%	1.6	0.1
11	ALL	98	0.40	0.46	4.3	0.5	53.1%	5.0%	1.0%	1.0%	2.5	0.3
12	ALL	104	0.79	0.54	10.9	1.0	78.8%	4.0%	18.3%	3.8%	6.1	0.7
ALL	DRY	743	0.17	0.48	3.1	0.2	31.0%	1.7%	2.6%	0.6%	1.5	0.1
ALL	WET	569	0.30	0.54	4.9	0.4	39.9%	2.1%	4.7%	0.9%	2.0	0.1
ALL	ALL	1312	0.22	0.51	3.9	0.2	34.8%	1.3%	3.5%	0.5%	1.7	0.1

Two-Way Analysis of Variance — Log10 Fecal Coliform Count (# / 100 ml)

	SS	DOF	MS	F	Prob(>F)
Total	347.2	1311	0.26		
Month	98.5	11	8.95	47.8	0.000
Precip.	5.6	1	5.61	30.0	0.000
Residual	243.2	1299	0.19		

MWRA Data, 1994-1999
DRY: 3-Day Antecedent Precipitation < 0.2 inches
WET: 3-Day Antecedent Precipitation >= 0.2 inches
SE = Standard Error of Mean

Table B - 7
Cosgrove Intake Fecal Coliforms vs. Year & Antecedent Precipitation

			Log-10 Mean		Arithmetic Mean		Frequency > 2		Frequency > 20		Geometric Mean	
Year	Precip	Count	Mean	Std_Dev	Mean	SE	Mean	SE	Mean	SE	Mean	SE
1994	DRY	123	0.11	0.44	2.4	0.3	23.6%	3.8%	0.8%	0.8%	1.3	0.1
1995	DRY	137	0.28	0.54	4.3	0.6	41.6%	4.2%	4.4%	1.7%	1.9	0.2
1996	DRY	130	0.10	0.43	2.1	0.2	29.2%	4.0%	0.0%	0.5%	1.3	0.1
1997	DRY	149	0.18	0.49	3.3	0.5	32.2%	3.8%	3.4%	1.5%	1.5	0.1
1998	DRY	150	0.13	0.45	2.7	0.4	26.0%	3.6%	2.0%	1.1%	1.3	0.1
1999	DRY	54	0.22	0.59	4.7	1.1	35.2%	6.5%	7.4%	3.6%	1.7	0.3
1994	WET	106	0.12	0.46	2.5	0.4	29.2%	4.4%	0.9%	0.9%	1.3	0.1
1995	WET	108	0.48	0.62	8.4	1.4	52.8%	4.8%	9.3%	2.8%	3.0	0.4
1996	WET	112	0.30	0.48	3.6	0.4	40.2%	4.6%	0.9%	0.9%	2.0	0.2
1997	WET	94	0.23	0.50	3.7	0.6	29.8%	4.7%	5.3%	2.3%	1.7	0.2
1998	WET	110	0.26	0.46	3.2	0.4	40.9%	4.7%	1.8%	1.3%	1.8	0.2
1999	WET	39	0.52	0.79	12.8	3.5	53.8%	8.0%	20.5%	6.5%	3.3	1.0
1994	ALL	229	0.11	0.45	2.4	0.2	26.2%	2.9%	0.9%	0.6%	1.3	0.1
1995	ALL	245	0.37	0.58	6.1	0.7	46.5%	3.2%	6.5%	1.6%	2.3	0.2
1996	ALL	242	0.19	0.46	2.8	0.2	34.3%	3.1%	0.4%	0.4%	1.6	0.1
1997	ALL	243	0.20	0.49	3.5	0.4	31.3%	3.0%	4.1%	1.3%	1.6	0.1
1998	ALL	260	0.18	0.46	2.9	0.3	32.3%	2.9%	1.9%	0.9%	1.5	0.1
1999	ALL	93	0.35	0.69	8.1	1.6	43.0%	5.1%	12.9%	3.5%	2.2	0.4
ALL	WET	743	0.17	0.48	3.1	0.2	31.0%	1.7%	2.6%	0.6%	1.5	0.1
ALL	DRY	569	0.30	0.54	4.9	0.4	39.9%	2.1%	4.7%	0.9%	2.0	0.1
ALL	ALL	1312	0.22	0.51	3.9	0.2	34.8%	1.3%	3.5%	0.5%	1.7	0.1

Two-Way Analysis of Variance   Log10 Fecal Coliform Count (# / 100 ml)

	SS	DOF	MS	F	Prob(>F)
Total	347.2	1311	0.26		
Year	11.2	5	2.25	8.9	0.000
Precip.	5.6	1	5.61	22.2	0.000
Residual	330.4	1305	0.25		

MWRA Data, 1994-1999
DRY: 3-Day Antecedent Precipitation < 0.2 inches
WET: 3-Day Antecedent Precipitation >= 0.2 inches
SE = Standard Error of Mean

Table B - 8
Sensitivity Analysis - Correlations of Intake Fecal Coliform Counts with Antecedent Rainfall

Sensivity to Sampling Agency & Protocol

	All Samples			Exceedence Freq.			Dry Samples				Wet Samples				ANOVA Results*		
Agency/Protocol	N	GM	CV	F>20	F > 2	F>0	N	GM	SE	F>20	N	GM	SE	F>20	Pr	Pr/Mo	Pr/Yr
MDC_INSIDE	164	1.8	1.24	1.8%	39%	64%	85	2.0	0.26	1.2%	79	1.6	0.23	2.5%	0.466	**	0.439
MDC_OUTSIDE	1068	2.2	1.26	6.2%	44%	75%	590	2.0	0.11	5.4%	478	2.5	0.14	7.1%	0.010	0.002	0.009
MWRA_INSIDE	1306	1.7	1.19	3.5%	35%	66%	740	1.5	0.06	2.6%	566	2.0	0.10	4.8%	0.000	0.000	0.000
MWRA_OUTSIDE	146	2.6	1.32	4.8%	51%	77%	86	2.3	0.32	4.7%	60	3.2	0.56	5.0%	0.115	0.074	**
Mean	1474	1.9	1.21	4.5%	42%	71%	826	1.7	0.07	3.6%	648	2.3	0.11	5.7%	0.000	0.000	0.000
MDC	1192	2.2	1.27	5.7%	43%	74%	659	2.0	0.10	5.0%	533	2.4	0.13	6.6%	0.029	0.004	0.026
MWRA	1312	1.7	1.19	3.5%	35%	66%	743	1.5	0.06	2.6%	569	2.0	0.10	4.7%	0.000	0.000	0.000
INSIDE	1329	1.7	1.19	3.6%	35%	66%	752	1.5	0.06	2.7%	577	2.0	0.10	4.9%	0.000	0.000	0.000
OUTSIDE	1079	2.2	1.27	6.0%	44%	76%	598	2.0	0.11	5.2%	481	2.5	0.14	7.1%	0.012	0.003	0.011

Sensitivity to Duration of Antecedent Rainfall

Antec. Period	Wet/Dry Criterion	All Samples			Exceedence Freq.			Dry Samples				Wet Samples				ANOVA Results*		
Days	inches	N	GM	CV	F>20	F > 2	F>0	N	GM	SE	F>20	N	GM	SE	F>20	Pr	Pr/Mo	Pr/Yr
1	0.07	1312	1.67	1.19	3.5%	35%	66%	879	1.6	0.06	3.1%	433	1.9	0.11	4.4%	0.026	0.001	0.016
2	0.13	1312	1.67	1.19	3.5%	35%	66%	798	1.5	0.06	2.6%	514	2.0	0.11	4.9%	0.000	0.000	0.000
3	0.20	1312	1.67	1.19	3.5%	35%	66%	743	1.5	0.06	2.6%	569	2.0	0.10	4.7%	0.000	0.000	0.000
4	0.27	1312	1.67	1.19	3.5%	35%	66%	685	1.4	0.06	2.3%	627	1.9	0.10	4.8%	0.000	0.000	0.000
5	0.33	1312	1.67	1.19	3.5%	35%	66%	649	1.5	0.06	2.2%	663	1.9	0.09	4.8%	0.000	0.000	0.000
6	0.40	1312	1.67	1.19	3.5%	35%	66%	603	1.5	0.07	2.5%	709	1.8	0.08	4.4%	0.003	0.000	0.003
7	0.47	1312	1.67	1.19	3.5%	35%	66%	566	1.5	0.07	2.5%	746	1.8	0.08	4.3%	0.052	0.001	0.047
8	0.53	1312	1.67	1.19	3.5%	35%	66%	533	1.5	0.08	2.6%	779	1.8	0.08	4.1%	0.187	0.008	0.174
9	0.60	1312	1.67	1.19	3.5%	35%	66%	514	1.5	0.08	2.7%	798	1.8	0.08	4.0%	0.327	0.013	0.310
10	0.67	1312	1.67	1.19	3.5%	35%	66%	502	1.6	0.08	3.0%	810	1.7	0.07	3.8%	0.999	0.110	0.999
14	0.93	1312	1.67	1.19	3.5%	35%	66%	426	1.6	0.09	2.3%	886	1.7	0.07	4.1%	0.764	0.068	0.745
18	1.20	1312	1.67	1.19	3.5%	35%	66%	388	1.6	0.10	3.6%	924	1.7	0.07	3.5%	0.388	0.742	0.336
22	1.47	1312	1.67	1.19	3.5%	35%	66%	344	1.6	0.10	3.5%	968	1.7	0.06	3.5%	0.652	0.451	0.601
26	1.73	1312	1.67	1.19	3.5%	35%	66%	309	1.6	0.11	5.2%	1003	1.7	0.06	3.0%	0.689	0.534	0.627

Sensitivity to Source of Climatologic Data

	All Samples			Exceedence Freq.			Dry Samples				Wet Samples				ANOVA Results*		
Source	N	GM	CV	F>20	F > 2	F > 0	N	GM	SE	F>20	N	GM	SE	F>20	Pr	Pr/Mo	Pr/Yr
MDC Wachusett	1312	1.67	1.19	3.5%	35%	66%	743	1.5	0.06	0.03	569	0.0	0.00	4.7%	0.000	0.000	0.000
Worcester Airport	1312	1.67	1.19	3.5%	35%	66%	737	1.5	0.06	0.03	575	0.0	0.00	4.5%	0.000	0.000	0.000
MDC / Air T > 32 deg F ***	1312	1.67	1.19	3.5%	35%	66%	815	1.6	0.07	0.03	497	0.0	0.00	3.6%	0.220	0.060	0.201

* ANOVA (Analysis of Variance) results are p values for precipitation effect; p < .05 indicates significant precipitation effect;
Pr = Precipitation alone, Pr/Mo = Precipitation controlled for monthly variations, Pr/Yr = Precipitation controlled for yearly variations

** insuffucient number of samples for performing ANOVA

*** defining wet samples using precipitation occuring on days when maximum air temperature at worcester airport exceeded 32 deg f
(an attempt to distinguish rainfall from snowfall)

Appendix C - Documents Considered in Preparing Testimony

1. MDC, Division of Watershed Management - Land Acquisition Fact Sheet (01 February 1998)

2. Part 3/Section 2.0 Watershed Protection - prepared by Camp Dresser & McKee

3. Staff Summary from Douglas B. MacDonald re: Submission of the Watershed Protection Interim Assessment Report for the Wachusett Reservoir Treatment Plan Project (September 7, 1998)

4. Wachusett Reservoir Watershed Protection Measures Appropriate With Filtration (June 1991)

5. Watershed Protection Plan for the MDC/MWRA Water Supply Source Executive Summary (June 1992) - prepared by MDC, MWRA and Rizzo Associates, Inc.

6. MDC/MWRA Water Supply System - Request for Review and Revision of DEP Determination that Filtration is Required for Wachusett Reservoir Pursuant to Paragraph 25 of Consent Order DEP File No. 92-513 (October 1, 1997) - prepared by MDC, MWRA and Camp Dresser & McKee

7. MWRA-Walnut Hill Water Treatment Project - Task 8: Integrated Water quality Improvement Strategy - Initial Assessment - June 1997

8. MDC - Watershed Protection Plan Update for Metropolitan Boston Water System - Wachusett Reservoir (Draft - July 31, 1998)

9. Watershed Protection Plan - Wachusett Reservoir Watershed (Dated: January 1991)

10. Investigation of Sources of Giardia and Cryptosporidium to Enhance Watershed Management for Wachusett Reservoir (4/95)

11. Wachusett Reservoir Pollution Investigation - Final Report: April 1987 - March 1988

12. Stormwater Treatment Alternatives for Wachusett Reservoir Shoreline (6/98)

13. Agricultural Best Management Practices Evaluation - Quabbin, Ware River and Wachusett Watershed

14. Gates Brook Treatment Feasibility Study Final Report (9/98)

15. MDC/MWRA Water Supply System - Submission of Confirmation Data - A Supplement to the October 1997 Request for Review and Revision of DEP Determination that Filtration is Required for Wachusett Reservoir Pursuant to Paragraph 25 of Consent Order DEP File No. 92-513 - Dated 10/30/98

16. Appendix of Exhibits Attached to October 30, 1998 MDC/MWRA Request for DEP Redetermination

17. United States EPA's Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources - March 1991 Edition

18. ENSR, Inc. 1998. *Gates Brook Treatment Feasibility Study*

19. French, J. 1988 MDC-DFWELE *Land Acquisition Program - MDC Watersheds*. Unpublished MDC report

20. Massachusetts DEP - Office of Watershed Management and MDC - Division of Watershed Management. 1994. *Gates Brook Stormwater Study (Wachusett Reservoir): 1990 through 1991.* Unpublished DEP/MDC report.

21. MDC - Division of Watershed Management. 1997. *Bird Harassment Program Fact Sheet.* Unpublished Report.

22. MDC - Division of Watershed Management. 1997. *Wildlife Fact Sheet.* Unpublished Report.

23. Proceedings of the American Water Works Association Convention. June 1997. *The Massachusetts Watershed Protection Act: Before and After Passage.*

24. SEA Consultants, Inc. February 1998. *MDC/DWM Innovative/Alternative Technology Pilot Program - 50% Design Submittal.*

25. Weston and Sampson Engineers, Inc. May 1998. *MDC Project No. WM97-061-D1A Preliminary Design Report Master Sewer Design - Phase II - Holden, MA - Phase 5.*

26. Weston and Sampson Engineers, Inc. May 1998. *MDC Project No. WM97-061-D1A Preliminary Design Report Master Sewer Design - Phase II West Boylston, MA - Phase 5*

27. Weston and Sampson Engineers, Inc. August 1997, Revised October 1997. *MDC Project No. WM97-061-D1A Preliminary Design Report Master Sewer Design - Phase II Holden, MA - Phases 3A & 3B*

28. Weston and Sampson Engineers, Inc. August 1997, Revised October 1997. *MDC Project No. WM97-061-D1A Preliminary Design Report Master Sewer Design - Phase II West Boylston, MA - Phase 3B*

29. Weston and Sampson Engineers, Inc. 1997. MDC *Project No. WM97-061-D1A Preliminary Design Report Master Sewer Design - Phase II - Holden, MA - Phase 4.*

30. Weston and Sampson Engineers, Inc. 1997. *MDC Project No. WM97-061-D1A Preliminary Design Report Master Sewer Design - Phase II - West Boylston, MA - Phase 4.*

31. Weston and Sampson Engineers, Inc. July 1996. *Report on MDC and Worcester Interceptor Capacity Analysis.*

32. MDC Land Acquisition Plan Wachusett Watershed - 1997-8. April 11, 1997

33. MDC/Watershed Management - Pure Water. *Water Quality Report 1988 Quabbin Reservoir and Wachusett Reservoir Watershed Monitoring Results*

34. MDC/Watershed Management - *Water Quality Report 1989 - Wachusett Reservoir Water Quality Data and Monitoring Results*

35. MDC/Watershed Management - *Water Quality Report 1990 - Wachusett Reservoir and Watershed Water Quality Data and Monitoring Results* - Lawrence A. Pistrang

36. MDC/Watershed Management - *Sanitary Survey 1990 - Southern Wachusett Sanitary District*

37. MDC/Watershed Management - *Sanitary Survey 1991 - Quinapoxet Sanitary District* - Lawrence A. Pistrang

38. MDC/Watershed Management - *Water Quality Report: 1991 - Wachusett Reservoir and Watershed* - Lawrence A. Pistrang, et al.

39. MDC/Watershed Management - *Sanitary Survey 1994 - Stillwater Sanitary District* - Lawrence A. Pistrang, et al.

40. MDC/Watershed Management - November 1993 - *Watershed Protection for Towns - Analysis of Existing By-Laws* - Lawrence A. Pistrang, et al.

41. Proposed Regulations - Planning Board Regulations for Performance Zone 1 - July 11, 1995

42. Town of Sterling Final Vote taken under ARTICLE 26 - to amend Protective (Zoning) By-Law - May 23, 1994

43. Commonwealth Research Group, Inc. - June 30, 1995 - *Task Memorandum Number Ten: Economic Impact Report on the Effects of the Watershed Protection Act (The Cohen Bill)*

44. Mass. Dept. Natural Resources - July 11, 1995 - *Quabbin Watershed: MDC Land Management Plan 1995-2004*

45. MDC/Watershed Management/Environmental Quality Section - *1992 Water Quality Report - Quabbin Reservoir Watershed and Ware River Watershed*

46. MDC/Watershed Management/Environmental Quality Section - *Water Quality Report: 1993 - Wachusett Reservoir and Watershed*

47. MDC/Watershed Management/Environmental Quality Section - *Water Quality Report: 1994 - Wachusett Reservoir and Watershed*

48. MDC/Watershed Management/Environmental Quality Section - *Water Quality Report: 1995 - Quabbin Reservoir Watershed and Ware River Watershed*

49. MDC/Watershed Management/Environmental Quality Section - *Water Quality Report: 1996 - Wachusett Reservoir and Watershed*

50. MDC/Watershed Management/Environmental Quality Section - *Water Quality Report: 1997 - Wachusett Reservoir and Watershed*

51. CDM - July 1995 - *Wachusett Reservoir Water Treatment Plan - Final Environmental Impact Report*

52. MDC/Watershed Management - *MDC Bird Harassment Program Wachusett Reservoir - Fall/Winter 1993-94 Program Summary Report* - John M. Scannell

53. MDC/Watershed Management - October 1993 - *Watershed Protection for Towns - A Guide to Bylaw Adoption*

54. Comprehensive Environmental Inc. - *Agricultural Best Management Practices Evaluation* - Quabbin, Ware River and Wachusett Watersheds

55. METLAND - January 1996 - *Stillwater River Drainage Basin Study - Analysis, Assessment, & Relationship of Critical Planning Issues*

56. METLAND - April 1996 - *APPENDICES FOR Stillwater River Drainage Basin Study - Analysis, Assessment, & Relationship of Critical Planning Issues*

57. Mass. Dept. Of Natural Resources - June 1996 - *Wachusett Watershed MDC Public Access Plan*

58. Copy of the January 12, 1999 letter from Paul R. Penner, Geographic Information Systems Coordinator, Division of Watershed Management

59. CD entitled "MassGIS Data Viewer Wachusett Reservoir Watershed"

60. 5-page document entitled, "Procedures for Installing MassGIS Data Viewer", last updated 12/23/98

61. Bound document entitled, "MassGIS Datalayer Descriptions and Guide to User Services", dated July 1997

62. 2-page document entitled, "MDC DWM Land Use/Land Cover Datalayer", dated January, 1999

63. 1-page document entitled, "MDC Division of Watershed Management Parcel Database Field Explanation, 4/98"

64. Metropolitan District Commission - Wachusetts Watershed Stormwater Management Plan - June 1998

65. MDC Stormwater Management Plan - Model Development and Application: Present and Future Land Uses - February 1998

66. A set of computer disks re: the reservoir system operations data for the Quabbin-Wachusett Reservoir System.

67. Judge Stearns' May 3, 1999 Memorandum and Order On United States' Motion For Partial Summary Judgment

68. Massachusetts Water Resources Authority - Waterworks Operations Department - Weekly Report - January 15, 1999

69. Letter dated April 15, 1999, from MWRA Legal Assistant Liz Steele to AUSA Henderson

70. MWRA Waterworks Operations Department Weekly Reports dated: February 26, 1999; March 5, 1999; March 12, 1999; March 19, 1999; April 2, 1999; and April 9, 1999

71. MWRA recent sampling results information distribution dated February 3, 1999

72. MWRA Water Quality Update information distribution dated February 23, 1999

73. MWRA Report on Wachusett Reservoir Source Water Fecal Coliform Testing dated February 12, 1999

74. Handouts from MWRA-DEP Meeting February 18, 1999

75. Memo from S. Estes-Smargiassi, MWRA to D. Terry, DEP re: Comparison of Fecal Coliform Results - dated February 23, 1999 (fax copy)

76. MWRA-DEP meeting Minutes February 23, 1999 - dated February 24, 1999

77. University of Massachusetts, *Miser Population Statistics*, www.umass.edu/miser/population/index/html

78. Declaration of Jennifer L. Clancy (1/27/99)

79. Declaration of David Ozonoff, MD, MPH (11/27/98)

80. Declaration of Jon Dahl (11/25/98)

81. Declaration of Richard W. Hull (11/30/98)

82. Second Declaration of J. Kevin Reilly (w/o Exhibits) (12/1/98)

83. Declaration of Edward J. Bouwer (11/30/98)

84. Declaration of Daniel A. Okun (11/30/98)

85. Declaration of Bruce E. Rittman (11/28/98)

86. MWRA's Motion for Leave to File Response to United States' Submission of New Information (3/1/99) with: (a) Response of the MWRA to United States' Submission of New Information;(b)Third Affidavit of Stephen Estes-Smargiassi;
87. (c)Second Affidavit of George W. Rutherford; and(d) Affidavit of Raymond Dittmer.

88. United States' Opposition to MWRA's Motion for Leave to File Response to United States' Submission of New Information (3/3/99) with Fifth Declaration of J. Kevin Reilly (3/3/99)

89. Second Affidavit of Stephen Estes-Smargiassi, with attachments

90. Project Report, September 1, 1996 through February 28, 1998, Development of Methods to Differentiate Microorganisms in MDC Reservoir Watersheds, March 30, 1998

91. Quarterly Report, Project Continuation: Development of Methods to Differentiate Microorganisms in MDC Reservoir Watersheds, December 15, 1998

92. EPA Comments on the DEP's Approval of the MWRA's Application to Avoid Filtration Under the Surface Water Treatment Rule

93. Memorandum entitled, "Analysis of Regulatory Authority to Control Storm Water in the Wachusett Reservoir Watershed," Prepared by EPA Region I, June 1999

94. Initial reports and rebuttal reports of United States' expert witnesses

95. Initial reports and rebuttal reports of MWRA expert witnesses.

MWRA Information Request Data
Submitted with September 1997 Information Request Response

Disk #	File Name	Description	Time Range	Format
1	1987.wk4 1988.wk4 1989.wk4 1990.wk4	spreadsheet of water quality of the Quabbin Reservoir and tributaries as measured by the MDC. parameters include sample #, code, site, date, turbidity, color, chloride, hardness, pH, alkalinity, DO, temp., Fe, conductivity, HPC, total coliform, fecal coliform, and chlorine residual	1/1/87 - 12/31/90	Lotus 123
2	1991.wk4 1992.wk4 1993.wk4 1994.wk4	spreadsheet of water quality of the Quabbin Reservoir and tributaries as measured by the MDC. parameters include sample #, code, site, date, turbidity, color, chloride, hardness, pH, alkalinity, DO, temp., Fe, conductivity, HPC, total coliform, fecal coliform, and chlorine residual	1/1/91 - 12/31/94	Lotus 123
3	1995.wk4 1996.wk4 1997.wk4 codestri.wk4 tryout-1.wk4 tryout-2.wk4 tie_in.wk4	spreadsheet of water quality of the Quabbin Reservoir and tributaries as measured by the MDC. parameters include sample #, code, site, date, turbidity, color, chloride, hardness, pH, alkalinity, DO, temp., Fe, conductivity, HPC, total coliform, fecal coliform, and chlorine residual. (codestri.wk4) - explanation of sample # and codes (tryout-1.wk4, tryout-2.wk4) - total and fecal coliform data from select Quabbin locations (tie_in.wk4) - unknown	1/1/95 - 5/30/97 1 - 5/96 1 - 5/97	Lotus 123
4	1987res.wk4 1988res.wk4 1989res.wk4 1990res.wk4 1991res.wk4 1992res.wk4 1993res.wk4	same water quality data for Quabbin Reservoir and tributaries as on dis #1, plus depth, pH, and specific conductivity	1/1/87 - 12/31/93	Lotus 123
5	1994res.wk4 1995res.wk4 1996res.wk4 1997res.wk4 codesres.wk4	same water quality data for Quabbin Reservoir and tributaries as on dis #1, plus depth, pH, and specific conductivity (codesres.wk4) - explanation of sample # and codes	1/1/94 - 5/30/97	Lotus 123
6	cl959697.wk4 cu-pb-97.wk4 ph959697.wk4 quart-96.wk4 quart-97.wk4	weekly chlorine residual monitoring results from MWRA community sample points (not community TCR locations) June 1997 Pb & Cu monitoring results weekly pH monitoring results corresponding to the chlorine residual results from the MWRA community sample locations water quality data including turbidity, color, odor, chloride, alkalinity, hardness, pH, cl2, temp., flow, specific conductivity, total coliform, and fecal coliform, from MWRA operational sampling locations including reservoirs, shafts, pump stations, labs and some communities	1/1/95 - 8/31/97 6/97 1/1/95 - 8/31/97 1/1/96 - 5/30/97	Lotus 123
7	rep-jan.wk4 thru rep-aug.wk4	table 1 - annual summary of community TCR results table 2 - monthly summary of community TCR results table 3 - daily cl2 results from 9 MWRA sampling locations table 4 - weekly cl2 results from MWRA community sample points corresponding to cl959697.wk4 above table 5 - monthly summary of community cl2 results associated with TCR monitoring table 6 - daily pH results from 9 MWRA locations in table 3 table 7 - daily total and fecal coliform data from MWRA source	1/1/96 - 8/31/96	Lotus 123

		water locations table 8 - daily turbidity at 5 MWRA monitoring locations table 9 - ICR data		
8	rep-sep.wk4 thru rep-dec.wk4	same as tables on disk 7	9/1/96 - 12/31/96	Lotus 123
9 & 10	rep-jan.wk4 thru rep-aug.wk4	same as tables on disk 7	1/1/97 - 8/31/97	Lotus 123
11	algae89.wk3 thru algae96.wk3	Wachusett Reservoir water column algae speciation and mineral sample results	1/1/89 - 12/31/96	Lotus 123
12	various files	Wachusett Reservoir (including Cosgrove Intake) and tributaries water quality sampling results including ammonia, phosphorus, conductivity, turbidity, pH, alkalinity, chloride, hardness, color, nitrate, nitrite, temp., nutrients, DO, fecal coliform, total coliform and insects.	1/1/90 - 12/31/91	Lotus 123
13	various files	Wachusett Reservoir (including Cosgrove Intake) and tributaries water quality sampling results including ammonia, phosphorus, conductivity, turbidity, pH, alkalinity, chloride, hardness, color, nitrate, nitrite, temp., nutrients, DO, fecal coliform, total coliform and insects	1/1/92 - 12/31/94	Lotus 123
14	various files	Wachusett Reservoir and tributaries water column profiles including nutrients, temp., DO, conductivity, pH, bacterial transects	1/1/95 - 12/31/96	Lotus 123
15	crpygiar.wk4	Wachusett Reservoir and tributaries sampling results for cryptosporidium and giardia	2/94 - 7/97	Lotus 123
16	cu-pb-92.wk4 cu-pb92e.wk4 cu-pb-97	community Pb & Cu monitoring results from two rounds of sampling 1992 and one round in 1997	6/92, 12/92, 6/97	Lotus 123
17	hpcdata.wk4	community HPC results	1/1/95 - 3/98	Lotus 123

MDC Data from Joe McGinn to Skip Hull - May 13, 1999

Disk 1	Agstm.xls Strmhdr.xls Strmpris.xls	1997 storm event monitoring from three trib impact areas including agricultural, residential, and pristine. Parameters measured include rainfall during event, fecal coliform, temp., and turbidity	1997	Microsoft Excel
Disk 2	Agstm.xls Strmhdr.xls Strmpris.xls	1997 storm event monitoring from three trib impact areas including agricultural, residential, and pristine. Parameters measured include rainfall during event, fecal coliform, temp., and turbidity	1997	Microsoft Excel
QTD	Q-may-84.wk1 Q-jun-84.wk1 Q-dec-85.wk1 Q-jul-95.wk1 Q-sept-95.wk1 Q-jun-	Quabbin transfer and meteorological information including flow from Quabbin to Wachusett and inflows from Ware and Swift rivers, temperature and rainfall data at Quabbin, and reservoir elevations	select months during 1984 - 1998	Lotus 123

	86.wk1 Q-apr-98.wk1			
CD-rom	GIS	GIS data		GIS

MDC Data Received at West Boylston from Larry Pistrang on May 20, 1999

18	95tribs.xls 96cosg.xls 96no3tp.xls 96qtrly.xls 96tribs.xls 97bacttr.xls 97cosg.xls 97final.xls 97no3tp.xls	tributary data for 1996 and 1997 including fecal coliform, turbidity, nutrients, total phosphorus. Bacterial transects from Wachusett. Cosgrove total and fecal coliform from inside and outside the intake. Quarterly monitoring data from tributaries including nutrients, turbidity, and total phosphorus. Wachusett water column profiles.	1995 - 1997	Microsoft Excel
19	97profil.xls 98bacttr.xls 98cosg.xls 98no3tp.xls 98profil.xls 98tr.xls 99trans.xls cosfec98.xls tribs1.xls tribs2.xls	same info as above for 1998 and 1999.	1998, 1999	Microsoft Excel
20	95cosg.xls 95qtrly.xls Still.xls Trout.xls Waush.xls Wboy.xls Wilder.xls	1995 Cosgrove intake bacteria data and quarterly monitoring for Wachusett including turbidity. 10 year tributary bacteria and nutrient data summarized.	1990 - 1999	Microsoft Excel
21	G-c9697.xls G-c99.xls all other tribs	1996 - 1999 giardia and crypto data for Wachusett tributaries. 10 year tributary bacteria and nutrient data summarized.	1990 - 1999	Microsoft Excel

Water Quality / Hydrology:

CRYP-GIA XLS
TURBIDIT XLS
CRYPGIAR XLS
ALGAE CSV
WQ1009 WK4
WQ1009B WK4
ORGANICS WK4
COSFC2 WK4
COSFC WK4
INTKBA~1 123
MWRA-TC- CSV
CRYPGIAR WK3
97TRIBWQ WK4
ICRFINAL WK4
PH959697 WK4
QUART-96 WK4
QUART-97 WK4
TURBIDIT WK4
COSGROVE WK3
92COLIF WK4
TRIBWQ WK4
92COLIF XLS
TRIBWQW WK4
TRIBWQ2 WK3
MSJCRY~2 WK4
RAINFALL WK4
HYDRAU~2 WK4
HYD_1997 MDB
HYDRAU~1 WK4
BACTRANS 123
BACTRANS WK4
TRIBS99 XLS
WACH ZIP
WACHCEM WQ1
WACHJUNK ZIP
WACHMDC ZIP
WACHMET WQ1
WACHREPT ZIP
WEFPAP ZIP
STORMW~1 DAT
WOR_PREC.TXT
AIR_TEMP.TXT
WQSUBSET WK4
INTKBA~1 123
Files of Form Q-Month-Year.WK1 for 1982-1999

STRMHDR3 XLS
STRMPRIS XLS
AGSTM1 XLS
AGSTM2 XLS
AGSTM3 XLS
STMPRIS2 XLS
STRMHDR1 XLS
STRMHDR2 XLS
TRIBEX WK1
90TRIBWQ WK3
91TRIBWQ WK3
92TRIBWQ WK3
93TRIBWQ WK3
94TRIBWQ WK3
96TRIBWQ WK3
1994 WK3
EPADB MDB
DETAIL~1 XLS
EFFECT~1 XLS

FTN Hydrodynamic Model:

CALIB87 EXE	TDISTR87 NPT	C_BR3_99 NPT
CALIB90 EXE	TFRENC87 NPT	C_BR4_99 NPT
CALIB92 EXE	TGATES87 NPT	C_BR5_99 NPT
CDISTR92 NPT	TGULLS87 NPT	C_BR6_99 NPT
CFRENC92 NPT	TMALAG87 NPT	C_QUAB87 NPT
CGATES92 NPT	TMALDE87 NPT	C_QUIN87 NPT
CGULLS92 NPT	TPRECP87 NPT	INITPR87 NPT
CMALAG92 NPT	TSTILL87 NPT	MET87 NPT
CMALDE92 NPT	TWAUSH87 NPT	QCOSGR87 NPT
CONFIR94 EXE	T_BR3_99 NPT	QDISTR87 NPT
CPRECP92 NPT	T_BR4_99 NPT	QFRENC87 NPT
CSTILL92 NPT	T_BR5_99 NPT	QGATES87 NPT
CWAUSH92 NPT	T_BR6_99 NPT	QGULLS87 NPT
C_BR3_99 NPT	T_QUAB87 NPT	QMALAG87 NPT
C_BR4_99 NPT	T_QUIN87 NPT	QMALDE87 NPT
C_BR5_99 NPT	W2_CON NPT	QPRECP87 NPT
C_BR6_99 NPT	BATH92H2 NPT	QSTILL87 NPT
C_QUAB92 NPT	CDISTR92 NPT	QWAUSH87 NPT
C_QUIN92 NPT	CFRENC92 NPT	QWDRAW87 NPT
README TXT	CGATES92 NPT	Q_BR3_99 NPT
GULBOY87 EXE	CGULLS92 NPT	Q_BR4_99 NPT
GULBOY90 EXE	CMALAG92 NPT	Q_BR5_99 NPT
GULBOY92 EXE	CMALDE92 NPT	Q_BR6_99 NPT
GULCUN94 EXE	CPRECP92 NPT	Q_QUAB87 NPT
OUT30087 EXE	CSTILL92 NPT	Q_QUIN87 NPT
OUT30090 EXE	CWAUSH92 NPT	QWAUSH92 NPT
OUT30092 EXE	C_QUAB92 NPT	QWDRAW92 NPT
OUT30094 EXE	C_QUIN92 NPT	Q_QUAB92 NPT
BATH87M2 NPT	MET92 NPT	Q_QUIN92 NPT
CDISTR87 NPT	QCOSGR92 NPT	TDISTR92 NPT
CFRENC87 NPT	QDISTR92 NPT	TFRENC92 NPT
CGATES87 NPT	QFRENC92 NPT	TGATES92 NPT
CGULLS87 NPT	QGATES92 NPT	TGULLS92 NPT
CMALAG87 NPT	QGULLS92 NPT	TMALAG92 NPT
CMALDE87 NPT	QMALAG92 NPT	TMALDE92 NPT
CPRECP87 NPT	QMALDE92 NPT	TPRECP92 NPT
CSTILL87 NPT	QPRECP92 NPT	TSTILL92 NPT
CWAUSH87 NPT	QSTILL92 NPT	TWAUSH92 NPT
W2 EXE 1	YLD-REP3 ALL	T_QUAB92 NPT
W2 FOR	YLD&SPIL MLB	T_QUIN92 NPT
W2 INC	YLD MLB	COMPILER OUT

Appendix D - Resume'

William W. Walker, Jr.

Date of Birth:

28 February 1949

Address:

1127 Lowell Road

Concord, Massachusetts 01742-5522

Tel: 508-369-8061

Fax: 508-369-4230

HomePage: http://www.shore.net/~wwwalker

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Education:

Massachusetts Institute of Technology

S.B. and S.M. in Chemical Engineering, 1971

Thesis: "A Pollution Model of the Charles River Basin"

University of California, Berkeley

Graduate Study in Chemical Engineering, 1971-72

Harvard University

Ph.D. in Environmental Engineering, 1977

Thesis: "Some Analytical Methods Applied to Lake Water Quality Problems"

Honorary Societies:

Tau Beta Pi - Engineering

Phi Lambda Upsilon - Chemistry

Professional Affiliations:

American Water Resources Association

North American Lake Management Society

Professional Awards:

Technical Excellence Award for Outstanding Research in Lake Restoration, Protection, & Management, North American Lake Management Society, 1988.

Designs for a Better Bay, Distinguished Award in Innovative Approaches to Stormwater Management, for Emerald Square Mall - Stormwater Management System, In Recognition of Outstanding Efforts to Promote and Develop Environmentally-Sensitive Land Use, State of

Rhode Island, April 1991 (with IEP, Inc., New England Development, GZA Geoenvironmental Technologies, Inc., Anderson-Nichols Inc., & Sumner Schein Architects & Engineers).

Certificate of Appreciation, U.S. Department of Justice, Office of the U.S. Attorney for Southern District of Florida, In Recognition of Outstanding Service and Dedication to the Cause of Everglades Ecosystem Preservation & Restoration, May 1994.

Specialization:

Water Quality Research & Engineering

Clients:

1997-	University of Wisconsin, Stevens Point
1996-	Michigan Department of Natural Resources
1998-	U.S. Attorney's Office, Department of Justice, Boston
1995-1997	Wisconsin Department of Natural Resources, Madison
1995-	U.S. Department of Interior, Everglades National Park
1995-1996	Water Department, Cambridge, Massachusetts
1995-	U.S. Department of Interior, Everglades National Park
1995	U.S. Department of Interior, Bureau of Reclamation, Denver
1994-1995	Metropolitan Water District of Southern California, Los Angeles
1993-1994	Town of China, Maine
1992-	South Florida Water Management District, West Palm Beach, Florida
1991-1995	Entranco Engineers / Herrera Env. Consultants/ Seattle Water Department
1991	City of New York, Water Supply
1990-1992	Black & Veatch, Kansas City, Missouri
1990-1992	Vadnais Lake Area Water Management Organization, Minnesota
1990-	Onondaga County, Dept. of Drainage and Sanitation, New York
1990	Piedmont Triad Regional Water Authority, North Carolina
1989-1994	U.S. Department of Justice, Washington, D.C.
1988-1990	Narragansett Bay Project, Providence, Rhode Island
1988-1990	Anderson-Nichols & Co., Inc., Boston, Massachusetts
1988-1989	City of Baltimore, Water Quality Management Office, Maryland
1988-1989	Maine Department of Environmental Protection, Lakes Program
1987-1990	Board of Health, Concord, Massachusetts
1987-1988	City of Worcester, Dept. of Public Works, Massachusetts
1987	Chickawaukie Lake Association, Camden & Rockland Water Co., Rockland, Maine
1986-1990	State of Oklahoma, Office of the Attorney General
1986-1989	State of Vermont, Department of State Buildings, Montpelier
1986-1988	Massachusetts Division of Water Pollution Control,Westboro

1986-1988	Upstate Freshwater Institute, Syracuse, New York
1986-1988	New York State Dept. of Environmental Conservation, Division of Fish & Wildlife
1986-1988	North American Lake Management Society, Washington, D.C.
1986-1987	Town of Lincoln, Rhode Island
1986-1997	Minnesota Pollution Control Agency, St. Paul
1985-1991	The Soap and Detergent Association, New York, New York
1985-1990	New England Development & Management, Inc., Newton, Massachusetts
1985-1989	Spaulding & Slye, Inc., Cambridge, Massachusetts
1985-1988	East Bay Municipal Utility District, Oakland, California
1984-1987	U.S. Environmental Protection Agency, Athens Research Lab
1984	City of Greenwood Village, Colorado
1983-1996	Environ Corporation, Washington, D.C. / East Bay Municipal Utilities District
1983-1993	Board of Water Commissioners, St. Paul, Minnesota
1983-1986	Cambridge Analytical Associates, Boston, Massachusetts
1983-1984	Metropolitan District Commission, Massachusetts
1983	FTN & Associates, Ltd., Little Rock, Arkansas
1983	National Council for Air & Stream Improvement, Inc., Medford, Massachusetts
1982-1990	IEP Inc., Northboro, Massachusetts
1982	Kleinschmidt and Dutting, Inc., Pittsfield, Maine
1981-1982	Meta Systems, Inc., Cambridge, Massachusetts
1980-1986	Vermont Department of Water Resources, Lakes Program, Montpelier
1980-1981	Environmental Defense Fund, Inc., New York
1978-1996	U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg
1978-1982	New Haven Water Company, Connecticut
1977-1980	Environmental Research & Technology Inc., Concord, Massachusetts
1977-	Stearns and Wheler, Inc., Cazenovia, New York
1976	National Academy of Science, Study Group on Environmental Monitoring

Employment Experience:

1975-1980	Environmental Engineer, Meta Systems, Inc., Cambridge, MA
1972-1975	Environmental Engineer, Process Research, Inc., Cambridge, MA
1970-1970	Process Design Engineer, The Badger Company, Cambridge, MA (summer)
1968-1969	Project Engineer, General Electric Co, Plastics Division, (summers) Pittsfield, MA
1967-1967	Laboratory Assistant, Hurlbut Paper Company, South Lee, MA (summer)

Patents:

"Soil Treatment Method", U.S. Patent Serial No. 434,322, 17 January 1974 (with S.Fogel, P.Foster, and P.Schenck).

"Production of Algal Biopolymers", U.S. Patent Serial No. 421,527 4 December 1973 (with S.Fogel, P.Foster, and P.Schenck).

Presentations & Project Reports:

"Combined Sewer Overflows to the Charles River Basin", prepared for the Metropolitan District Commission, Massachusetts, by Process Research Inc., 1972.

"The Impacts of Aquatic Weed Harvesting on Hardy Pond", prepared for Conservation Commission, Town of Waltham, Massachusetts, by Process Research, Inc. 1972.

"The Effects of Algae on Soil Structure", Process Research, Inc., 1974.

"Optimization, Error, and Sensitivity Analysis in Ecosystem Modeling", Technical Paper Number 750401, Onondaga Lake Modeling Project, Environmental Systems Program, Harvard University, April 1975.

"Characteristics and Behavior of Sensitivity Equations in an Ecosystem Model", Technical Paper Number 750407, Onondaga Lake Modeling Project, Environmental Systems Program, Harvard University, April 1975.

"Techniques for Parameter Estimation in Nonlinear Dynamic Systems Applied to Two Ecosystem Models", Technical Paper Number 750401, Onondaga Lake Modeling Project, Environmental Systems Program, Harvard University, April 1975.

"The Impact of the Federal Water Pollution Control Act on the Charles River and Boston Harbor", prepared for the National Commission on Water Quality by Process Research, Inc., 1975.

"Final Report on the Storrow Lagoon Demonstration Project", prepared for the Metropolitan District Commission, Massachusetts, by Process Research, Inc., 1975.

"Environmental Impact of the Cross-Florida Barge Canal: Nutrient Budget" prepared for the U.S. Army Corps of Engineers, Jacksonville District, by Meta Systems, Inc., August 1975.

"Mapping and Modeling", presented at "A Seminar and Workshop on Water Monitoring Technology", sponsored by EPA Region III, Environmental Research and Technology, Inc., and the University of Delaware, College of Marine Studies, May 1976.

"Roles of Monitoring Data in Formulating Environmental Management Policy: A Case Study of Syracuse/Onondaga Lake", prepared for the Panel on Ambient Monitoring, Study Group on Environmental Monitoring, Committee on National Statistics, National Acad. of Science, June 1976.

"Exploring the Onondaga Lake Data Base", Technical Paper 760609, Onondaga Lake Modeling Project, Environmental Systems Program, Harvard University, June 1976.

"Displays of Vertical Temperature, Chloride, and Density Gradients in Onondaga Lake, 1968-76: Description of Methods and Interpretation of Results", prepared for Stearns and Wheler, Civil and Sanitary Engineers, Cazenovia, New York, July 1977.

"Water Quality Impacts of the Proposed Expansion of the SHERCO Coal-Fired Power Facility", prepared for the State of Minnesota by Environmental Research and Technology, Inc., 1977.

"Street-Cleaning Dynamics" and "Storage/Treatment Optimization for Storm/Combined Sewers" in "Water Quality Goals and Objectives - Boston Case Study" prepared for Council on Environmental Quality, Washington, by Environmental Research and Technology, Inc., 1977.

"A Preliminary Analysis of the Potential Impacts of Watershed Development on the Eutrophication of Lake Chamberlain", prepared for New Haven Water Company, Connecticut, by Meta Systems, Inc., June 1978.

"Control of Agricultural Nonpoint Source Pollution", presented at the National Conference on Environmental Engineering, American Society of Civil Engineers, Kansas City, Missouri, July 1978 (with R.A.Sharpin, J.J.Wineman, and J.Kuhner).

"Methodology for Evaluating Low-Flow Augmentation as a Water Quality Control Measure", prepared for Water Planning Division, U.S. Environmental Protection Agency, by Meta Systems, Inc., July 1978.

"Modeling the Land-Water Interaction: Needed for Evaluation of Best Management Practice Effects on Water Quality", presented at the North Atlantic Regional Meeting, American Society of Agricultural Engineers, Paper No. NA78-207, August 1978 (with J. Kuhner).

"A Preliminary Analysis of Water Quality Problems in the Lower Winooski", prepared for the U.S. Environmental Protection Agency, Water Planning Division, by Meta Systems, Inc., February 1979.

"Land Use/Reservoir Eutrophication Relationships in the West River System: Data Analysis and Monitoring Program Design", prepared for New Haven Water Company, Connecticut, by Meta Systems, Inc., March 1979.

"An Oxygen-Based Trophic State Index", presented at the North American Lake Management Conference, Michigan State University, sponsored by U.S. Environmental Protection Agency, Clean Lakes Program, April 1979.

"Documentation of the Meta Systems Version of the QUAL-II Water Quality Simulation Model", prepared for U.S. Environmental Protection Agency, Water Planning Division, by Meta Systems Inc., July 1979.

"Calibration and Application of QUAL-II to the Lower Winooski River: Preliminary Studies", prepared for U.S. Environmental Protection Agency, Water Planning Division, by Meta Systems Inc., July 1979.

"Costs and Water Quality Impacts of Reducing Agricultural Nonpoint Source Pollution: An Analysis Methodology", prepared for the U.S. Environmental Protection Agency, Athens Environmental Research Laboratory, by Meta Systems, Inc., EPA-600/5-79-009, August 1979.

"Numerical Characterization of Reservoir Hypsiographic Curves", prepared for the U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, EWQOS Work Unit 1-E, Working Paper No. 1, November 1979.

"Inventories of Data Suitable for Empirical Modeling of Reservoir Eutrophication", prepared for the U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, EWQOS Work Unit 1-E, Working Paper No. 2, December 1979.

"Copper Sulfate Use and Effects - A Literature Review", prepared for New Haven Water Company, Connecticut, by Meta Systems, Inc., 1979.

"Wachusett Mountain Ski Area Environmental Impact Study", prepared for the Massachusetts Department of Environmental Management, by Wallace, Floyd, Ellenzweig, & Moore, Inc., Meta Systems, Inc., Interchange, and Cambridge Acoustical Associates, Inc., 1980.

"Variability of Trophic State Indicators in Reservoirs: Implications for Design of Data Reduction Procedures", prepared for the U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, EWQOS Work Unit 1-E, Working Paper No. 3, March 1980.

"Analysis of 1979 Monitoring Data from Land Use/Water Quality Studies in the West River System", prepared for New Haven Water Company, Connecticut, by Meta Systems, Inc., 1980.

"Evaluation of Methods for Estimating Phosphorus Loadings from Grab-Sample Concentration and Continuous Flow Data", prepared for the U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, EWQOS Work Unit 1-E, Working Paper No. 4, May 1980.

"Variability of Trophic State Indicators in Reservoirs", in "Restoration of Lakes and Inland Waters", U.S. Environmental Protection Agency, Office of Water Regulations and Standards, EPA-440/5-81-010, December 1980.

"A Lake Eutrophication Analysis Procedure Applied to Lake Morey", prepared for the Vermont Agency of Environmental Conservation, Water Quality Division, Lakes Program, September 1980.

"Compilation, Review, and Analysis of Historical Water Quality Data from Lake Quinsigamond, Massachusetts (Task 2)", prepared for the Massachusetts Department of Environmental Quality Engineering and U.S. Environmental Protection Agency, Nationwide Urban Runoff and Clean Lakes Programs by Environmental Design and Planning, Inc. and Meta Systems, Inc., August 1980.

"Estimation of Volume/Area/Elevation Curves for CE Reservoirs", prepared for the U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, EWQOS Work Unit 1-E, Working Paper Number 5, October 1980.

"Estimation of Hydrologic Budgets for CE Reservoirs", prepared for the U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, EWQOS Work Unit 1-E, Working Paper No. 6, December 1980.

"Eutrophication and Related Water Quality Impacts of the Proposed Columbia Dam: Data Compilation and Analysis", prepared for the Environmental Defense Fund, Inc., in support of testimony before the Tennessee Water Quality Control Board regarding Section 401 Certification of the TVA Columbia Dam Project, Duck River, Tennessee, December 1980.

"A SAS Interface for QUAL-II", prepared for G.K.Y. Associates and the Vermont Agency of Environmental Conservation, December 1980.

"Preliminary Assimilative Capacity Analysis of the Duck River Below the Proposed Columbia Dam", prepared for the Environmental Defense Fund, Inc., in support of testimony before the Tennessee Water Quality Control Board regarding Section 401 Certification of the TVA Columbia Dam Project, Duck River, Tennessee, January 1981.

"Estimation of Nutrient Budgets for CE Reservoirs", prepared for the U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, EWQOS Work Unit 1-E, Working Paper No. 7, January 1981.

"Analysis of 1980 Monitoring Data from Land Use/Water Quality Studies in the West River Basin", prepared for New Haven Water Company, Connecticut, by Meta Systems, Inc., March 1981.

"A Compilation of Empirical Eutrophication Models", prepared for U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, EWQOS Work Unit 1-E, Working Paper No. 8, April 1981.

"Water Quality Data Analysis, Model Development, and Model Applications for Lake Quinsigamond, Massachusetts", prepared for Meta Systems, Inc., Environmental Design and Planning, Inc., Massachusetts Department of Environmental Quality Engineering, and U.S. Environmental Protection Agency, Nationwide Urban Runoff and Clean Lakes Programs, May 1981.

Empirical Methods for Predicting Eutrophication in Impoundments - Report 1: Data Base Development", "prepared for Office, Chief of Engineers, U.S. Army, Washington, D.C., Technical Report E-81-9, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, May 1981.

"Water Quality Issues Related to Small Hydropower Development", presented at the "Engineering Foundation Conference on Small Hydropower Development", Henneker, New Hampshire, July 1981.

"Empirical Methods for Predicting Eutrophication in Impoundments - Report 2: Model Testing", prepared for Office, Chief of Engineers, U.S. Army, Washington, D.C., Technical Report E-81-9, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, September 1982.

"QUAL-II Enhancements and Calibration to the Lower Winooski", prepared for the Vermont Agency of Environmental Conservation, Water Quality Division, Montpelier, December 1981.

"Calibration of LEAP to Vermont Lakes, Interim Report: Data Base Summary and Preliminary Model Testing", prepared for the Vermont Agency of Environmental Conservation, Water Quality Division, Lakes Program, Montpelier, December 1981.

"Land Use/Water Quality Relationships in the West River System, Connecticut", Final Report, prepared for New Haven Water Company, Connecticut, by Meta Systems, Inc., Cambridge, Massachusetts, January 1982.

"Calibration and Testing of a Eutrophication Analysis Procedure for Vermont Lakes", Final Report, prepared for Vermont Department of Water Resources and Environmental Engineering, Lakes Program, Montpelier, January 1982.

"Documentation for Water Quality Models Developed in the Lake Quinsigamond 314/NURP Project", prepared for Meta Systems, Inc., Environmental Design and Planning, Inc., Massachusetts Department of Environmental Quality Engineering, and U.S. Environmental Protection Agency, Nationwide Urban Runoff and Clean Lakes Programs, March 1982.

"MODELER - A Modeling and Data Management System for Microcomputers", Computer Software and Documentation, March 1982.

"Screening Procedures for Assessment of Hydropower Water Quality Impacts", prepared for Vermont Agency of Environmental Conservation, Department of Water Resources and Environmental Engineering, Montpelier, Vermont, June 1982.

"Water Quality Impacts and Assessment Procedures for Hydropower Projects", presented at the Northeast Coldwater Workshop, American Fisheries Society, New York Chapter, Cornell University, published in Hydropower Development and Fisheries: Impacts and Opportunities, New York State Department of Environmental Conservation, G.A. Barnhart, ed., June 1982.

"Review of Proposed Waste Load Allocations for the Corinna Discharge to the Upper East Branch of the Sebasticook River", prepared for Kleinschmidt and Dutting, Inc., Pittsfield, Maine, July 1982.

"A Model for Predicting Longitudinal Gradients in Reservoir Trophic State Indicators", prepared for Environmental Laboratory, USAE Waterways Experiment Station, Vicksburg, Mississippi, EWQOS Work Unit 1-E, Working Paper No. 9, July 1982.

"A Simplified Method for Predicting Phosphorus Gradient Potential in Reservoirs", prepared for Environmental Laboratory, USAE Waterways Experiment Station, Vicksburg, Mississippi, EWQOS Work Unit 1-E, Working Paper No. 10, August 1982.

"Oxygen Depletion / Trophic Status Relationships in CE Reservoirs", prepared for Environmental Laboratory, USAE Waterways Experiment Station, Vicksburg, Mississippi, EWQOS Work Unit 1-E, Working Paper No. 11, October 1982.

"Structure and Calibration of an Error Analysis Framework for The Vermont Lake Eutrophication Analysis Procedure", prepared for the Vermont Agency of Environmental Conservation, Water Quality Division, Lakes Program, November 1982.

"Calibration and Application of QUAL-II to the Upper East Branch of the Sebasticook River between Corrinna and Coburn", prepared for Kleinschmidt and Dutting, Inc., Pittsfield, Maine, November 1982.

"Some Recent Adaptations and Applications of QUAL-II in the Northeast", in Barnwell, T.O., ed., "Proceedings of the Stormwater and Water Quality Model Users Group Meeting, January 27-28, 1983", University of Florida, Gainesville, U.S. Environmental Protection Agency, Athens, Georgia, EPA-600/9-83-015, September 1983.

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