Firm Yield Estimator – Version 1.0 Software Documentation

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June 30, 2000

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1 Introduction

The Firm Yield Estimator - Version 1.0 (FYE) is a software tool for use in estimating the firm yield of Massachusetts surface water reservoir systems. The software is designed to assist communities in fulfilling the requirements of the Massachusetts Water Management Act which requires communities permitting surface water supplies to demonstrate the ability to meet their projected demand by estimating the firm yield of the reservoir system based on the 1960's drought-of-record. The algorithms employed by the software are those recommended by the Massachusetts Department of Environmental Protection (DEP) in its January 1996 Guidance Document entitled "Estimating the Firm Yield of a Surface Water Reservoir Supply System in Massachusetts" (DEP, 1996).

The program is menu-driven, and help files are available to lead the user through the appropriate steps to develop an estimate for the firm yield of a surface water reservoir or a system of surface water reservoirs. The program assists the user in performing a reservoir yield scanning analysis to determine whether synthetically generated precipitation and streamflow data are necessary for the firm yield assessment. If any reservoir in the system does not refill at any point during at least 15% of the years examined in the scanning analysis, the program will generate the 1,000-year sequence of precipitation and streamflow data that is required for the firm yield assessment.

After performing the scanning analysis, the user can then perform the firm yield analysis using either actual meteorological and streamflow data or the synthetic data developed in the scanning analysis. The program is linked to a database of temperature, precipitation, and snowfall data from meteorological stations in Massachusetts (as well as some bordering locations in Rhode Island, Connecticut, New York, Vermont, and New Hampshire). The program is also linked to a database of U.S.G.S. (United States Geological Survey) streamgauge data for sites across Massachusetts. The user has the option of selecting a meteorological station and streamgauge location from the databases or supplying his or her own data. Additional information about the reservoir system (such as required releases from the reservoir, peak use factors, withdrawals by other users, watershed elevation, soil retention, channel slope factors, *etc.*) are entered by the user in standard Windows dialog boxes or through input files specified in such dialog boxes. The user can also specify the relationship between the area of the reservoir and the volume of water in the reservoir.

The software is capable of producing output in a form that partially satisfies the requirements of materials that must be submitted to DEP in support of a reservoir system yield assessment. The program can produce plots (both on-screen and hard-copy) of the reservoir storage *vs.* time. The program is also capable of producing summary files of the data used in the firm yield analysis. These files identify the options that were selected and the meteorological and streamflow data that were used in the firm yield analysis. The software can also produce data files containing a table of reservoir storage versus time.

The software includes helpfiles that contain all of the information presented in Chapter 2 of this software documentation and training manual. Using only the help files, users can develop firm yield estimates in the absence of this training manual.

2 Technical documentation

2.1 Installation

The FYE is designed to run on any computer running Microsoft's Windows 95, Windows 98, or Windows 2000. The FYE is installed by simply copying the file *FirmYld.exe* from the CD-ROM to a directory on the hard drive. If desired, a shortcut to the FYE can be placed on the desktop using Windows Explorer. To start the program, double click the file in Windows Explorer, or select *Run* from the Windows *Start* menu and enter the filename.

The remaining directories on the CD-ROM contain the meteorological and streamflow databases. These files can either be copied to the hard drive, or they can be accessed directly from the CD-ROM.

2.2 Program startup

Upon initial startup, the FYE will display a title screen with a menu across the top of the program window and three buttons at the bottom, labeled *Continue*, *Close*, and *Credits*. All menu options are inactive while the title screen is displayed with the exception of the *Exit* option on the *File* menu and the *Help* options. Selecting *File|Exit* will close the FYE. Selecting *Help* will activate the Windows Help for the FYE and will allow the user to search the electronic version of the FYE's documentation.

Clicking on the *Continue* button erases the title screen, activates many of the menu options, and displays key information about the reservoir system being analyzed. The top section of the screen summarizes the meteorological data that are currently being used in the analysis including the name of the meteorological station used in the analysis, the years of meteorological data used, and the completeness of the meteorological data set. The next section summarizes streamflow data including the name of the stream gauge used in the analysis and the years of streamflow data that are used. The third section summarizes reservoir-specific data that have been entered by the user, showing whether reservoir characteristics, bathymetry data, withdrawals by other users, peak use factors, and evaporation rates have been specified. Initially, the screen display will indicate only that no information has been entered. The bottom section of the screen summarizes (in bold type) which analyses have been performed for the reservoir. If a firm yield analysis has already been performed for the reservoir system, the estimated firm yield of the reservoir will appear in this section.

Clicking on the *Close* button closes the FYE program. This performs the same action as selecting *Exit* from the *File* menu or clicking the close button in the top right corner of the program window.

Clicking on the *Credits* button displays a dialog box containing information about the software developer, database developer, and a photo credit for the image on the title screen. Click the *Ok* button to close the dialog box and return to the title screen.

2.3 File management

File management in the FYE is controlled through use of the *File* menu. After the *Continue* button is pressed on the title screen, the title screen is erased, and all of the options on the *File* menu are activated. Three menu items relate to file management, *Open*, *Close*, and *Save*. A fourth option, *Summary File*, saves a file summarizing the firm yield analysis. The fifth option, at the bottom of the *File* menu is *Exit*.

Selecting *File|Open* brings up a standard Windows dialog box for opening files. Select a previously created FYE file from this dialog box to modify or review an analysis. The default extension for files is *.fye*, and files with this extension in the current directory will automatically be listed in the open file dialog box. To list all files with any extension in this dialog box, select "All Files (*.*)" from the list box at the bottom of the dialog box, then click *Open*. Only one reservoir can be analyzed at a time. (Analysis of a system of reservoirs is handled with the options in the *System* menu.) Hence, if a new file is opened while an analysis for a second reservoir system is being performed, the FYE will display a warning message if the analysis for the second reservoir system has not been saved. The warning message gives the user the option of saving the existing analysis prior to opening the file, erasing the existing analysis prior to opening the file, or canceling the operation.

File|Close closes the existing analysis and erases all input data. *File|Close* does not save the analysis. To save a firm yield analysis, select *File|Save*.

File|Save opens a standard Windows dialog box for saving files. Specify the directory in which the file should be saved and the filename, then click the *Save* button. The default filename extension for firm yield analyses is *.fye*. Select the *Cancel* button to return to the FYE without saving the data file. After clicking the *Save* button, the FYE displays a dialog box that allows the user to specify a title for the analysis and any comments that the user wishes to include in the data file. After entering the title and comments, click the *Ok* button to save the data file.

File|Summary file opens a standard Windows dialog box for saving files. This option is disabled if a firm yield has not yet been calculated for the reservoir or if the user changes input data without recalculating the firm yield of the reservoir. Specify the directory in which the file should be saved and the filename, then click the *Save* button. The default file type for the summary file is a Text file with a filename extension of *.txt*. Select the *Cancel* button to return to the FYE without saving a summary file. Appendix C contains a sample summary file from the FYE.

File|Exit closes the FYE. This performs the same action as selecting the standard Windows close button marked with an x in the top right corner of the program window.

2.4 Accessing meteorological and streamflow databases

Accessing meteorological data and streamflow data from the databases that accompany the FYE is done through the *Data* menu. The topmost section of the *Data* menu contains three options pertaining to meteorological data. The second section contains three options that allow access to streamflow data.

2.4.1 Meteorological data

The *Data|Preprocess NOAA data* option is used to update the databases that accompany the FYE. Selecting this option allows the user to start with the ASCII Cooperative Summary of the Day TD3200 (Tape Deck 3200) data files obtainable from the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA) and process meteorological data into a format that can easily be read by the FYE. Data in TD3200 format can be purchased from NOAA on CD-ROM. Daily meteorological data available for all meteorological stations in a state are in a single data file. These data include air and soil temperatures, rainfall, snowfall, and evaporation. A detailed description of this data format can be obtained from NOAA upon request.

After selecting the *Preprocess NOAA data* option, an open file dialog box will appear on the screen. Select the meteorological data file that contains data on the stations of interest. Because NOAA's default file extension for TD3200 meteorological data files is *.dat*, this is the default extension in the open file dialog box. After selecting the data file, a select directory dialog box will appear. Specify the drive on which the preprocessed meteorological files will be saved, and then select the directory in which the files will be saved by double-clicking on the appropriate directory (the file folder icon next to the directory in which the files will be saved will show an open file folder). Click *Ok* to begin preprocessing the meteorological data.

On the CD-ROMs containing the NOAA meteorological data, in addition to the meteorological data file, NOAA provides a station inventory file (file extension *.inv*). The inventory file contains station names and specifies which data were collected at each station during each year. The inventory file is not necessary for the FYE to preprocess meteorological data, but because the data file itself identifies meteorological stations by number and not by name, the FYE will not have access to the station names if the inventory file is not available. The FYE searches for the inventory file in the same directory in which the meteorological data file is located. If the inventory file is located by the FYE, meteorological station names will be added to the preprocessed meteorological data files; otherwise, the station name in the preprocessed files will be a blank line. On the June 1995 CD-ROM for New England meteorological stations (NOAA, 1995a), the data file for Massachusetts is named *MA19STN.DAT* and the inventory file is named *MA19STN.INV*.

Preprocessing meteorological stations for a state could take several minutes for states with large numbers of meteorological stations (the meteorological file for New York contains data for several hundred meteorological stations and is 307 MB in size). The FYE will not allow the user to access any of the menu items until meteorological data preprocessing is complete. The FYE will save one file for each meteorological data station in the specified directory. The filename for each meteorological data file consists of the station number for the meteorological station followed by the extension *.met*. For example, the filename for the preprocessed meteorological data file for Boston's Logan International Airport (station number 190770) is *190770.met*.

The meteorological data files included with the FYE as the meteorological database are preprocessed data files. See Chapter 4 for a detailed description of the meteorological database. Appendix A contains a sample of a preprocessed meteorological data file.

Data|Input meteorological data allows the user to specify the name of a file containing preprocessed meteorological data for use in the firm yield analysis. After selecting this option, an open file dialog box will appear. The default file extension for preprocessed meteorological files is *.met*. Select the appropriate file and click *Open*. After opening the file, the meteorological station name, years for which meteorological data are available, and the completeness of the meteorological data set will be displayed in the main window of the FYE.

Data|Select met file from list allows the user to select a meteorological station from a list of stations by name. A select directory dialog box will appear asking the user to specify a directory containing preprocessed meteorological data files. The FYE will then search the directory for all files with the *.met* extension and will list the station names in a list box. Scroll down the list of meteorological stations and select the desired station, then click *Ok*. After opening the file, the meteorological station name, years for which meteorological data are available, and the completeness of the meteorological data set will be displayed in the main window of the FYE.

After selecting a meteorological data file using either the *Data|Input meteorological data* or the *Data|Select met file from list* option, if complete temperature, precipitation, and snowfall data are not available for every month in the period of record, the FYE displays a dialog box asking the user how to accommodate missing data. The user is presented with four options for replacing missing data. The first option is to replace missing data with an average value for that month, calculated from all available data. If, for example, precipitation data are missing for February 1968, the FYE will calculate the average precipitation for February in all other years, and use that value in place of the missing February 1968 value. Naturally, this option could not be used if precipitation data were missing for February of every month in the period of record. In this case, the FYE would prompt the user to select an alternate method for replacing missing data. The second option is to replace missing data with meteorological data from a nearby meteorological station. The FYE will prompt the user to enter a meteorological data station to use for replacement data. First, the FYE displays a dialog box asking the user to select the directory in which the meteorological data files are stored. The FYE then displays a dialog box listing all available meteorological stations in that directory. Select the desired meteorological station and click *Ok*. If all missing data cannot be replaced using the alternate data file, the FYE prompts the user to select another method (or simply another meteorological station) to use to replace data that are still missing. The third option is to replace missing data by interpolating between months that have data. This is most useful when only a few data points are missing, because interpolated data can be wildly inaccurate if, for example, all data were missing between

February 1968 and February 1969, and the FYE interpolated temperature data for all missing months based on temperatures in February 1968 and February 1969. The fourth, and final, option is to replace missing data by using the data from the previous year (or most recent year for which data are not missing). If February 1968 precipitation data are missing, the FYE replaces this value with the precipitation measured in February 1967. If data from the first year of the dataset are missing, the FYE instead uses data from the first subsequent year for which data are available.

2.4.2 Streamflow data

To estimate the firm yield of a surface water reservoir, one must know the surface water inflow to the reservoir. Ideally, one would have a stream gauge on the stream or river that feeds the reservoir; however, data from such a stream gauge seldom exist. In the absence of a stream gauge on the desired stream, it is desirable to identify a nearby unregulated stream or river and to use those data combined with information about the watersheds for both the gauged stream and the reservoir stream to estimated surface water inflow to the reservoir. The options discussed in this section allow the user to specify streamflow data that can be used to estimate inflow to the reservoir.

Data|USGS streamflow data allows the user to specify a USGS streamflow data file to use for streamflow data in the firm yield analysis. Selecting this option brings up an open file dialog box. Select the directory containing the streamflow data files, select the appropriate file, and click *Open*. The default file extension for USGS streamflow files is *.txt*. The file format for the USGS data files is that in which they can be obtained directly from the USGS website (http://water.usgs.gov). See Chapter for a detailed description of this file format and see for a sample streamflow data file.

Data|Select USGS file from list is similar to the *Data|Select met file from list* option and allows the user to select a stream gauge location by name from a list of streamgauge locations. Upon selecting this option, a select file dialog box will appear asking the user to select the directory in which the USGS data files are saved. Select a drive and double click on a directory to highlight it (the file folder icon should show an open folder) then click *Ok*. The FYE will search the directory for USGS data files with a *.txt* extension and will list the station names in a list box. Scroll down the list of streamflow stations and select the desired station, then click *Ok*. After opening the file, the stream gauge name and years for which streamflow data are available will be displayed in the main window of the FYE.

Data|Other streamflow data is a means of entering streamflow data if data are not available in the USGS format. To use this option, the user must create a data file of streamflow data in a specified format. The file should use only ASCII characters. All blank lines and lines beginning with the pound sign “#” are treated as comments and are ignored by the FYE. The first line of the file (other than comment lines) should be the name of the location where the streamflow measurements (or estimates) were made. Subsequent lines should contain a month (an integer between 1 and 12), a year (all four digits), and the total monthly streamflow in units of millions of gallons per month. The first few lines of a sample data file could read:

```
#This is a data file containing monthly streamflow
#data for Aber’s Creek near the proposed reservoir
#site.
#Streamflow data are in units of millions of gallons
#per month
#
Aber’s Creek
1 1960 223
2 1960 302
3 1960 440
4 1960 365
5 1960 478
6 1960 298
```

etc.

2.5 Entering reservoir-specific properties

The five options at the bottom of the *Data* menu allow the user to enter reservoir-specific properties necessary for estimating the firm yield of the reservoir. These options can also be accessed by clicking on the blue hypertext links on the main screen of the FYE. The options are divided into two groups. The first contains only the *Data|Reservoir characteristics* menu item. The reservoir characteristics accessed by this selection (as well as a meteorological station and a stream gauge location) must be specified prior to transforming the streamflow data from the stream gauge into estimated inflows to the reservoir (using the *Calculate|Transform USGS data* option). The remaining four options (*Data|Bathymetry*, *Data|Evaporation rates*, *Data|Peak use factors*, and *Data|Withdrawals by other users*) must be specified prior to performing a scanning analysis (*Calculate|Perform scanning analysis*) or a firm yield analysis (*Calculate|Estimate firm yield*) of the surface water reservoir. On the main window of the FYE, the information under the heading “Other Data” allows the user to quickly determine which data have and have not been supplied.

Selecting the *Data|Reservoir characteristics* option displays a dialog box on the screen that allows the user to enter the area of the watershed supplying the reservoir (in square miles), the area of the watershed contributing to streamflow at the stream gauge (also in square miles), and the usable capacity of the reservoir (in millions of gallons). Additionally, the dialog box asks the user to specify required release rates from the reservoir.

Four radio buttons allow the user to select from four possibilities for specifying release rates. The four radio buttons are labeled *No required releases*, *Constant release rate*, *Release rate varies by month of year*, and *Specify release rates in a text file*. Selecting the *No required release* button automatically sets required releases equal to zero when estimating the firm yield of the reservoir. Selecting *Constant release rate* sets the required releases equal to the specified value for every month of the period used to calculate the firm yield. Selecting *Release rate varies by month of year* brings up a dialog box in which the user can specify required release rates for each month of the year. Specify the release rates by month and then click *Ok* to close the monthly release rate dialog box. Finally, selecting *Specify release rates in a text file* brings up an open file dialog box in which the release rate file can be specified. This option is useful if the required release rates change from year to year. The format of the release rate file is the similar to the format for *Other streamflow data* discussed in Section 2.4.2 above. Lines beginning with the pound sign (#) are treated as comments and are ignored. All other lines should begin with a month (an integer between 1 and 12), a four-digit year, and the required release rate in millions of gallons for the month. A sample of the first few lines of a release rate file appears below:

```
#The first three lines of this file are comments
#Release rates are given in millions of gallons per
#month
3 1955 57.8
4 1955 80
5 1955 30.4
6 1955 57.8
7 1955 28.6
8 1955 40.2
etc.
```

The FYE performs a few checks on the data entered in the reservoir characteristics dialog box. The areas of the reservoir and stream gauge watersheds must both be greater than zero, but less than the total area of Massachusetts (7,838 square miles). The volume of the reservoir must be a positive number in millions of gallons. If a constant release rate is specified or if release rates are specified by month, all specified release rates must be between 0 and 100,000 million gallons.

When the *Data|Bathymetry* option is selected, the FYE will display a dialog box in which the user can specify a polynomial that will be used to estimate the surface area of the reservoir as a function of the volume of usable water in the reservoir. DEP's guidance document (DEP, 1996) recommends fitting a third order (or higher) polynomial to bathymetry data. First, specify the order of the polynomial that will be used to estimate reservoir surface area from the volume of usable water in the reservoir. Then, enter the best-fit coefficients for the polynomial. The polynomial will be of the form:

$$A = C + C_1 S + C_2 S^2 + C_3 S^3 + \ldots$$

where A is the surface area of the reservoir in square miles, and S is the usable volume of water in the reservoir in millions of gallons. The coefficients C, C_1, C_2, C_3, etc. are the constant coefficient, linear coefficient, quadratic coefficient, cubic coefficient, etc. The polynomial cannot be of order greater than nine. Note that S is the volume of *usable* water in the reservoir, not the total volume of water in the reservoir.

Data|Evaporation rates allows the user to specify evaporation rates for the reservoir. Clicking on this menu item will create an evaporation rates dialog box. Two radio buttons at the top of the dialog box allow the user to select between specifying evaporation rates by month or estimating evaporation rates directly from meteorological data. If *Specify monthly evaporation rates* is selected, specify monthly evaporation rates in inches for each month in the bottom section of the dialog box. Each evaporation rate specified must be greater than or equal to zero. If *Estimate evaporation from meteorological data* is selected, evaporation rates will be estimated from the meteorological data. If this option is selected when no meteorological data have been entered, the FYE will display a warning message and will then ask the user to either specify monthly evaporation rates or to enter meteorological data before attempting to estimate evaporation rates. If meteorological data have already been entered, the FYE will prompt the user to enter the longitude of the reservoir (in decimal degrees) and the elevation of the reservoir (in feet). See Appendix 2: Estimating Reservoir Evaporation of the DEP guidance document (DEP, 1996) for a detailed description of the algorithm used to estimate reservoir evaporation from meteorological data. To view the evaporation rates that have been estimated, after specifying the longitude and elevation and clicking *Ok*, click on *Data|Evaporation rates* again. *Estimate evaporation from meteorological data* will remain selected, but the calculated evaporation rates will appear in the bottom section of the dialog box.

Data|Peak use factors allows the user to enter peak use factors for withdrawing water from the reservoir. These values account for seasonal variations in withdrawal rates from the reservoir. Default values for the peak use factor are 0.7 for January through March, 0.9 for April, 1.2 for May, 1.4 for June, 1.5 for July, 1.3 for August, 1.1 for September, 0.9 for October, and 0.8 for November and December. These default peak use factors are those recommended by DEP (2000) for use in the firm yield analysis and describe a typical scenario in which summer withdrawal rates from the reservoir will be higher than average while winter withdrawal rates will be lower. The peak use factors must all be greater than or equal to zero, and the average of the twelve peak use factors should be 1.0. If the sum of the monthly peak use factors falls outside the range of 11.9 to 12.1, the FYE displays an error message and asks the user to correct the data. After specifying the peak use factors, click *Ok* to continue with the analysis.

Data|Withdrawals by other users allows the user to enter withdrawal rates from the reservoir by other users of water. Selecting this menu item will display a dialog box very similar to the one for peak use factors. Specify monthly withdrawal rates in millions of gallons per day, then click *Ok*. All withdrawal rates should be greater than or equal to zero. By default, the withdrawal rates for other users for all months are zero, representing a scenario in which there are no other users of reservoir water.

2.6 Estimating reservoir system yields

The *Calculate* menu contains options that allow the user to perform a scanning analysis of a reservoir and estimate the firm yield of a surface water reservoir. Additional options allow the user to estimate surface water inflows to a surface water reservoir from daily streamflow data or to generate 1,000 years of meteorological data using the bootstrapping technique described in DEP's guidance (1996).

2.6.1 Transform USGS data

The first option on the *Calculate* menu is the *Transform USGS data* option. This option generates flow rates for a stream based on meteorological data, streamflow data for a nearby stream, and information about the reservoir and watersheds. Because the calculations are based on meteorological data, streamflow data, and reservoir characteristics, the *Calculate|Transform USGS data* menu item cannot be accessed until these data have been entered. Because inflow to the reservoir must be known before the firm yield of the reservoir can be estimated, the *Perform scanning analysis*, *Generate meteorological data*, and *Estimate firm yield* options on the *Calculate* menu remain inaccessible until the streamflow data are transformed.

Upon selecting *Transform USGS data*, a dialog box will be displayed requesting information about the reservoir watershed. Enter the average watershed elevation (feet), the mean channel slope (feet/mile), and the maximum soil retention (inches) for the surface water reservoir. See Chapter 3 of the DEP guidance (1996) for a description of how to calculate the mean channel slope and the maximum soil retention. By default, the FYE will calculate average annual precipitation and average annual snowfall from the meteorological data, but if these do not represent a best estimate of precipitation in the vicinity of the reservoir, the user can select the appropriate radio buttons and specify values for average precipitation and snowfall. On the rare occasions when the stream gauge is located at the inflow to the reservoir, check the box labeled *Streamgauge data can be used directly in the firm yield analysis* and click *Ok*. In this case, it is not necessary to specify any additional information in the dialog box.

The FYE performs minimal checking on the entries in the dialog box. The watershed elevation must be greater than 0 and less than 3,487 feet (the highest elevation in Massachusetts). The mean channel slope must be between 0 and 5,000 feet/mile, and the maximum soil retention must be between 0 and 100 inches. Average annual precipitation and snowfall must both be between 0 and 200 inches.

After entering all data in the dialog box, the FYE will estimate inflows to the surface water reservoir. The algorithm used to calculate the inflows is the QPPQ transform described in detail in Chapter 3 of the DEP guidance (1996). After surface water inflows to the reservoir have been estimated, the text at the bottom of the FYE main window will indicate that the transform has been performed, and the options to perform a scanning analysis and to generate 1,000 years of meteorological data will be activated.

2.6.2 Scanning analysis

A scanning analysis generates a rough estimate of the reservoir firm yield by using several simplifying assumptions. The primary reason for performing the scanning analysis is to determine whether the firm yield assessment requires the use of synthetically generated precipitation and streamflow data to supplement measured data. DEP has determined that if a reservoir does not refill at least one month a year during 15% or more of the years in the scanning analysis period of record, a 1,000 year long sequence of streamflow and precipitation data is required in the firm yield assessment. The reason for this is to ensure that the firm yield analysis is performed using data from a sufficiently long period-of-record that includes the most important climate and streamflow sequences which occur during the very worst possible droughts. The assumed initial condition of a full reservoir at the start of the first month of the simulation has been shown to measurably influence the firm yield estimate, unless the inflow sequence is 500 more years long for large storage reservoirs. Flow records for sufficiently unregulated stream gauge locations are generally much less than 100 years in length.

The scanning analysis does not account for precipitation to or evaporation from the reservoir surface. Additionally, monthly peak use factors are set at 0.9 for January through March, 1.1 for July through September, and 1.0 for all remaining months. The equation used to estimate the yield of the reservoir in the scanning analysis is:

$$S(j) = Q_{si}(j) - a(j)n(j)Q_y - Q_r(j) - Q_{so}(j) + S(j-1)$$

where the terms are:

- $S(j)$ water in active storage at the end of month j (millions of gallons);
- $Q_{si}(j)$ streamflow into the reservoir in month j (millions of gallons);
- $\forall(j)$ peak use factor for month j;
- $n(j)$ number of days in month j (days);
- Q_y scanning analysis reservoir firm yield (millions of gallons per day);
- $Q_r(j)$ required release rate for month j (millions of gallons);
- $Q_{so}(j)$ uncontrolled reservoir release rate in month j (millions of gallons); and
- $S(j-1)$ water in active storage at the end of the previous month (millions of gallons).

The streamflows into the reservoir (Q_{si}) are the transformed streamflow values calculated when the *Calculate|Transform USGS data* option is selected. Required releases are the values specified in the *Data|Reservoir characteristics* dialog box. Uncontrolled reservoir releases are anything in excess of the total reservoir capacity specified in the *Data|Reservoir characteristics* dialog box. The reservoir is assumed to be at full capacity at the beginning of the first month in the analysis. To calculate the scanning analysis yield, the FYE iterates over the scanning yield, Q_y. A small value is selected for Q_y, and the amount of water in active storage during each month of the simulation is calculated. If the reservoir never empties during the simulation, Q_y is incrementally increased and the simulation is repeated until the reservoir is empty during exactly one month in the simulation. The value of Q_y during the simulation when the reservoir empties once during the simulation is the scanning yield of the surface water reservoir. For a more detailed description of the scanning yield calculation, see Chapter 4 of the DEP guidance document (1996).

The FYE presents a graph of the scanning yield results in a new window. The date is plotted on the x-axis, and reservoir storage is plotted along the y-axis (as a percentage of reservoir capacity). The percentage of years in the simulation during which the reservoir did not completely refill is displayed below the graph, as is the estimated scanning yield of the reservoir. To copy the graph and paste it into another application such as a word processing application, select *Copy* from the *Graph* menu at the top of the graph window. To print the graph, select the correct printer and print orientation on the *Graph|Printer setup* dialog box, and then select *Graph|Print*. To close the graph window, click on the *Close* button at the bottom of the window. An example graph of the results of the scanning analysis appears in Figure 2.1 below.

After the scanning analysis has been performed, the scanning yield of the surface water reservoir appears at the bottom of the main program window.

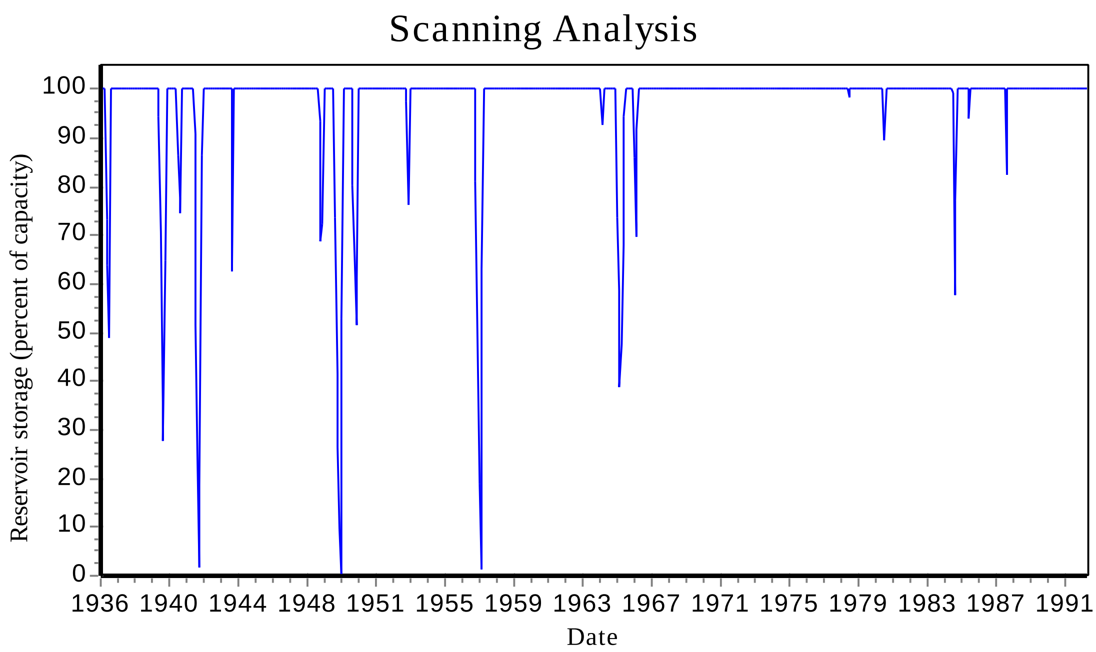

Figure 2.1 Graph of the scanning analysis results.

2.6.3 Generate 1,000 years of meteorological data

Ideally, the firm yield analysis for a reservoir would be performed using a very long period of record that includes climate and streamflow sequences that occurred during the very worst possible droughts. In reality, even the longest periods of record are usually less than 100 years in length, sometimes much less. If the scanning analysis demonstrates that the reservoir does not refill for at least one month a year in 15% or more of the period of record, DEP requires that a 1,000 year sequence of meteorological and streamflow data be used in the firm yield analysis.

The 1,000 year sequence of meteorological and streamflow data is generated using a sampling technique termed “bootstrapping” in Chapter 6 of DEP’s guidance (1996). The period of record for which both meteorological and streamflow data are available is divided into two year periods each beginning in the month of April and ending in March, two years later. Five hundred two year periods are then selected at random from the entire period of record, resulting in 1,000 years of data. See the DEP guidance for a more detailed description of the bootstrapping technique and the reasons behind it.

To generate the 1,000 year sequence of data, select *Calculate|Generate meteorological data*. A dialog box will appear asking whether the 1,000 years of data should be generated from the entire period of record or from only a subset of the data. Specify the subset of the period of record which should be used to generate the 1,000 year sequence of data, then click *Ok*. The 1,000 year sequence of data will be generated, as will be indicated at the bottom of the main window of the FYE.

2.6.4 Estimating the firm yield

The *Calculate|Estimate firm yield* option calculates the firm yield for the reservoir or reservoir system. This option will not be accessible until all data necessary to perform the analysis have been entered. These data include meteorological data, streamflow data, reservoir characteristics, bathymetry data, withdrawals by other users, peak use factors, and evaporation rates. Additionally, the streamflow data transform must have been performed to estimate inflows to the reservoir, and a scanning analysis must have been performed. If the scanning analysis indicates that the reservoir does not refill at least once during 15% of the years in the period of record, a 1,000 year sequence of meteorological data must also be generated before the firm yield can be calculated. Selecting *Calculate|Estimate firm yield* brings up a dialog box that allows the user to select between using actual meteorological data or the 1,000 year series of generated data. If the user specifies that actual data should be used in the analysis, the FYE asks the user to specify the years to use in the analysis. The maximum range is the period of overlap for meteorological and streamflow data. The analysis will begin in April of the first year specified and will end in March of the last year specified.

The firm yield of the reservoir system is estimated using an algorithm similar to that for the scanning analysis, but including terms to account for precipitation on and evaporation from the reservoir surface. Additionally, site-specific peak use factors are employed instead of using default values. The equation used to estimate the firm yield of the surface water reservoir is:

$$S(j) = A_r(j)[P(j) - E_p(j)] + Q_{si}(j) - \boldsymbol{a}(j)n(j)Q_y - Q_r(j) - Q_{so}(j) + S(j-1)$$

where the terms are the same as in Section 2.6.2 with the following additions:

- $A_r(j)$ reservoir surface area in month j;
- $P(j)$ total precipitation in month j; and
- $E_p(j)$ total evaporation from the reservoir surface in month j.

Additionally, Q_y is now the estimated firm yield for the reservoir instead of the scanning yield. The inputs to the equation above are those that were previously entered in the dialog boxes accessed by using the *Data* menu. To calculate the firm yield, the FYE iterates over the yield, Q_y. A small value is selected for Q_y, and the amount of water in active storage during each month of the simulation is calculated. If the reservoir never empties during the simulation, Q_y is incrementally increased and the simulation is repeated until the reservoir is empty during exactly one month in the simulation. The value of Q_y during the simulation when the reservoir empties once during the simulation, when multiplied by a correction factor, is the firm yield of the surface water reservoir. The correction factor adjusts for the error in the firm yield estimate made using a monthly time step model (as opposed to a smaller time step). This corrected firm yield estimate is:

$$Q_y = \frac{Q_y(\Delta t = 1\ \text{month})}{1 + A_o e^{(B_o S_{\max}^{0.67})}}$$

where the terms are:

Q_y	firm yield estimate (million gallons per day);
)t	time step;
S_{max}	active reservoir storage capacity (millions of gallons);
A_o	constant (0.0696); and
B_o	constant (-0.0589).

For a more detailed description of the firm yield calculation and correction factor, see Chapter 7 of the DEP guidance document (1996).

The FYE presents a graph of the firm yield analysis results in a new window. The date is plotted on the x-axis, and reservoir storage is plotted along the y-axis (as a percentage of reservoir capacity). The estimated firm yield of the reservoir is displayed beneath the graph. To copy the graph and paste it into another application such as a word processing application, select *Copy* from the *Graph* menu at the top of the graph window. To print the graph, select the correct printer and print orientation on the *Graph|Printer setup* dialog box, and then select *Graph|Print*. To close the graph window, click on the *Close* button at the bottom of the window. An example graph of the results of the firm yield analysis appears in Figure 2.2 below.

After the scanning analysis has been performed, the scanning yield of the surface water reservoir appears at the bottom of the main program window.

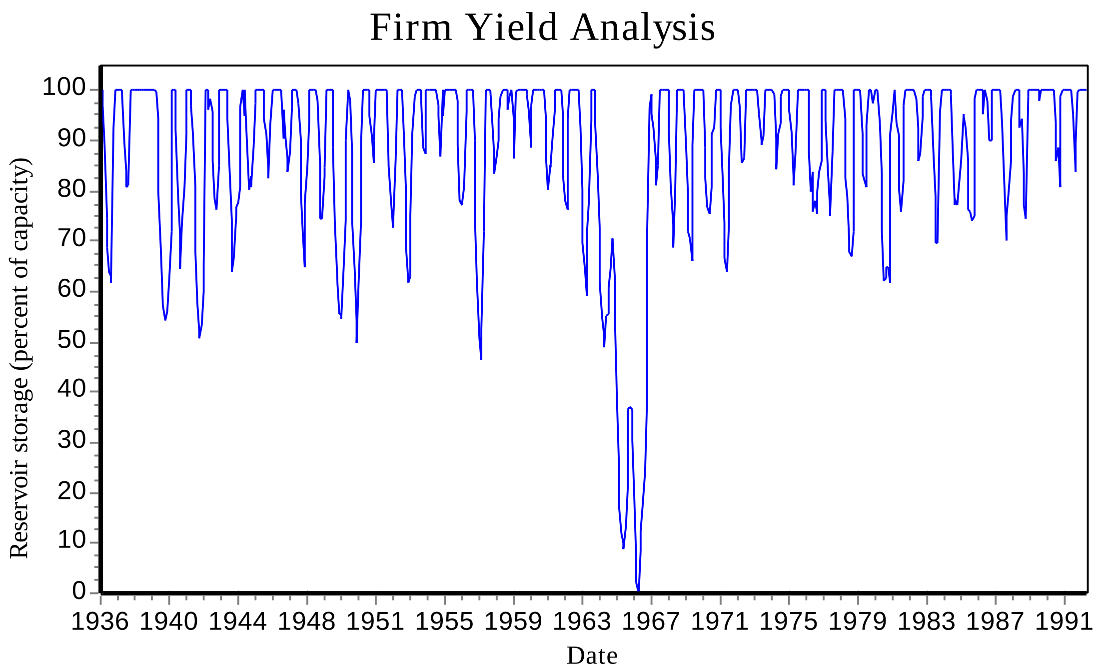

Figure 2.2 Graph of sample firm yield analysis results.

2.7 Reservoir system analysis

The options beneath the *System* menu heading are used when performing a firm yield analysis of a system of reservoirs. Because the analysis of a system of reservoirs requires detailed information about each individual reservoir in the system, the FYE requires that a firm yield analysis be performed for each reservoir in the system prior to calculating the yield of the system. The information in the saved data files for the individual reservoirs is then used to estimate the yield of the system of reservoirs.

The first step in performing a yield analysis for a reservoir system is to specify the reservoirs in the system using the *System|Load reservoir data* option. After this option is selected, the FYE will display a dialog box asking for the number of reservoirs in the system and for the datafile associated with each reservoir. The FYE can be used to estimate yields for reservoir systems consisting of between two and ten reservoirs in series or parallel (or a combination of the two). Specify the number of reservoirs in the system in the text box at the top of the dialog box. Then for each reservoir in the system click the *Data File* button. Clicking the *Data File* button brings up a standard Windows dialog box for opening files. Select the appropriate data file then click *Open*. The FYE will check to make sure the file is a Firm Yield Estimator file and will check that all necessary data for the reservoir are contained in the file. The FYE will then display an error message if data are incomplete or will return to the *Load reservoir data* dialog box. The *Load reservoir data* dialog box will display the title given to each reservoir after the file has been specified. Specify the data files for each reservoir in the system, then click *Ok*.

The *System relationships* option is used to specify the relationships between reservoirs in the system and to specify the meteorological data to use in the analysis. This option is disabled until all necessary data have been specified in the *Load reservoir data* dialog box. The *System relationships* dialog box contains a list box for each reservoir in the system. For each reservoir in the system, click on the down arrow at the right side of the list box, and select the destination for outflow (both required releases and uncontrolled spills) from that reservoir. As an example, consider a two reservoir system where the outflow from Reservoir 1 flows into Reservoir 2. In this example, the user would specify “Reservoir 2" as the destination for outflow from Reservoir 1, and “None” as the destination for outflow from Reservoir 2. At the bottom of the dialog box, select a radio button indicating whether actual meteorological data should be used in the analysis or whether a 1,000 year sequence of data should be used in the analysis. If *Use actual meteorological data* is selected, the period of analysis will be the period of overlap for meteorological data, streamflow data, and require release data for all the reservoirs in the system. If *Generate a 1,000 year series of meteorological data to use in the analysis* is selected, the 1,000 year series will be generated by selecting 500 two-year sequences of data from the period of overlap, as discussed in Chapter 6 of DEP’s guidance (1996).

The *Estimate system yield* option calculates the firm yield of the system of reservoirs. This option is disabled until the data in the *Load reservoir data* and *System relationships* dialog boxes are complete. The yield of the system of reservoirs is calculated as specified in Section 7.6 of DEP’s guidance document (1996). The yield of the system of reservoirs is displayed in a small dialog box. Click *Ok* to close this dialog box. With few exceptions, the firm yield of the system of reservoirs will be greater than or equal to the sum of the firm yields of the individual reservoirs in the system.

System|Save system opens a standard Windows dialog box for saving files. Specify the directory in which the file should be saved and the filename, then click the *Save* button. The default filename extension for firm yield system analyses is *.fys*. Select the *Cancel* button to return to the FYE without saving the data file.

System|Open system opens a standard Windows dialog box for opening files. Specify the file containing the saved system analysis, then click the *Open* button.

2.8 Help files

All information included in the technical documentation for the software is also available in the help files accompanying the FYE. Select *Help* from the menu at the top right of the main FYE window, or click on any of the help buttons that appear in most of the dialog boxes created by the FYE. It is then possible to search the help files for specific topics or to scan through the table of contents to identify topics of interest.

3 *Tutorial – Example case*

This tutorial introduces a reservoir in Massachusetts and leads the user through an analysis of the firm yield of the surface water reservoir. First, the user selects a nearby meteorological station and stream gauge and enters reservoir specific data into the FYE. The tutorial leads the user through a transformation of the streamflow data into inflow data for the reservoir. The user then performs a scanning analysis, generates 1,000 years of meteorological and streamflow data, and finally, performs the firm yield analysis for the reservoir.

Upon starting the FYE, the title screen of the FYE is displayed with a menu at the top and three buttons at the bottom. Click the *Continue* button to proceed. The title screen of the FYE is shown in Figure 3.1 below.

Figure 3.1 The title screen of the Firm Yield Estimator

The FYE will then display information about the reservoir under analysis in the main program window. The top two sections contain information about the meteorological and streamflow stations selected for the analysis. The third section lists reservoir specific sets of parameters and whether or not they have already been entered. The bottom section summarizes in boldface the analyses that have been performed on the reservoir and the results (if available). Figure 3.2 shows the main window of the FYE immediately after running the program and clicking the *Continue* button.

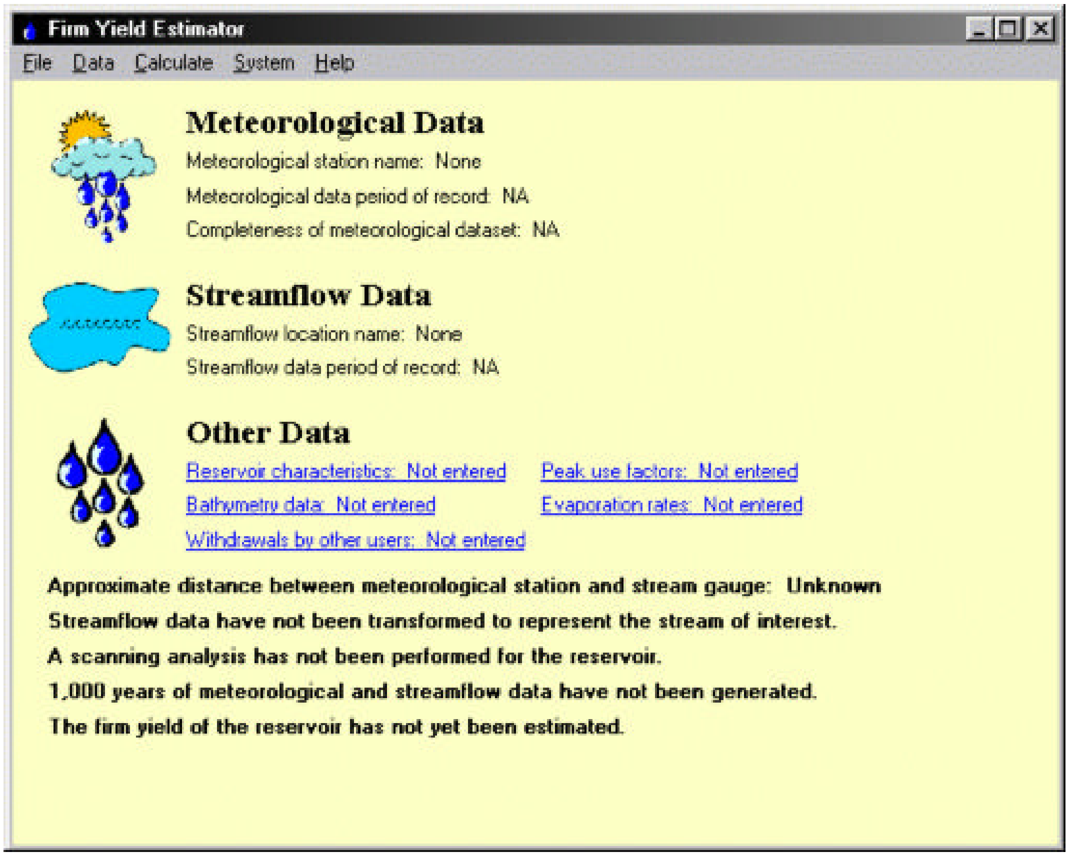

Figure 3.2 The main window of the FYE immediately after clicking *Continue*

The hypothetical reservoir considered in the tutorial is a 1 billion gallon reservoir located near Amherst, Massachusetts.

The first step in performing the firm yield analysis is to select an appropriate nearby meteorological station and stream gauge. Table 4.1 lists all meteorological stations included in the FYE database. Factors that should be included in this decision include proximity to the reservoir, years for which data are available, and completeness of the meteorological data set, among others. The meteorological station at Amherst would clearly be an appropriate station to use for the hypothetical reservoir. To select this station, click on the *Data* menu at the top of the FYE window, and select the *Select met file from list* option. The FYE will then open a dialog box asking the user to select the directory in which the meteorological data files are stored. The meteorological data files are on the FYE CD-ROM. Select the CD-ROM drive from the list box (or the appropriate drive if the files have been transferred to the hard drive) underneath the "Drive:" heading, then double-click on the directories until reaching the Met\MA directory which contains the data files for Massachusetts meteorological data stations. At this point, the folder next to the MA directory should be open as shown in Figure 3.3 below. Then click the *Ok* button.

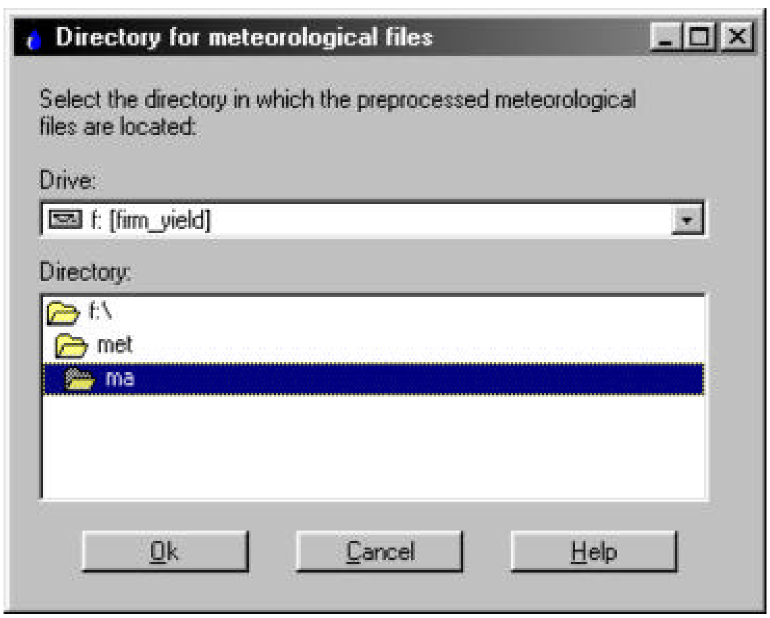

Figure 3.3 Selecting the meteorological files directory

The FYE will display a dialog box in which the meteorological station an be selected from the list of all stations in the specified directory (see Figure 3.4). Select the “AMHERST” station from the list, then click *Ok*. Information about the meteorological station will now be displayed in the main window of the FYE.

Figure 3.4 Selecting the meteorological data station

The FYE will then display a dialog box stating that meteorological data are missing for several months. Select the radio button next to *Replace missing data with average values for that month*, then click *Ok*. The meteorological data are now complete.

The procedure for selecting a stream gauge is very similar to that for selecting a meteorological station. First select an appropriate stream gauge for the analysis. Factors that should influence the decision are proximity to the reservoir, the years for which data are available, and the extent to which streamflow is regulated above the stream gauge, among other factors. Tables 4.3 and 4.5 can assist in the decision making process, but DEP should be consulted regarding the selection of an appropriate stream gauge to use in the firm yield analysis. The Mill River At Northampton, Ma is an appropriate station to use for the hypothetical reservoir. Select the *Data|Select USGS file from list* option from the menu, specify the directory containing the streamflow data files (in the Stream\MA directory on the CD-ROM), then select “Mill River At Northampton, Ma” from the list and click *Ok*. Information about both the selected meteorological station and the selected stream gauge will now be displayed in the main window of the FYE. The distance between the meteorological station and the streamgauge (in this case 7.7 miles) will also be displayed.

The next step in performing the firm yield analysis is to enter descriptive characteristics of the reservoir and watersheds. Select *Data|Reservoir characteristics* from the menu of the FYE. The dialog box shown in Figure 3.5 will be displayed on the screen. Enter the areas of the reservoir watershed, the watershed contributing to the stream gauge, and the reservoir capacity. Specify the area of the reservoir watershed to be 5.85 square miles, the area of the stream gauge watershed to be 54 square miles, and the usable reservoir capacity to be 1,000 million gallons (1.0 billion gallons). The analysis will assume that there are required releases from the hypothetical reservoir totaling 18.6 million gallons per month, so select the *Constant release rate* radio button, enter the release rate of 18.6 million gallons in the edit box, and click *Ok*.

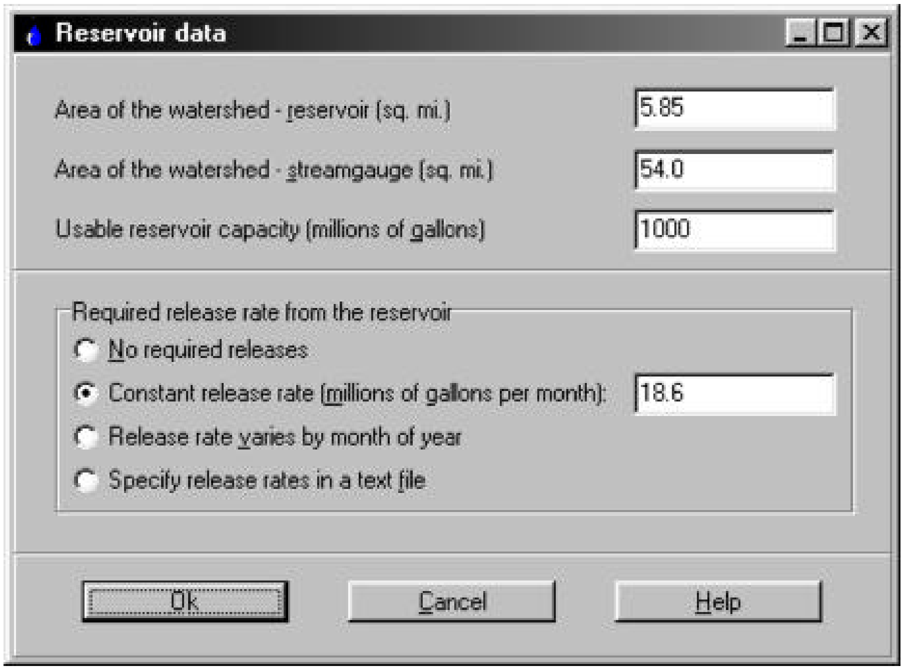

Figure 3.5 Reservoir characteristics dialog box

Next, select *Data|Bathymetry* from the menu to show the bathymetry dialog box displayed in Figure 3.6 below. The area of a surface water reservoir becomes smaller as the amount of water in the reservoir decreases (while the area of the reservoir's watershed increases by the same amount). The DEP guidance (1996) requires that a continuous approximate mathematical relationship be developed between reservoir surface area and reservoir storage, and suggests that developing a mathematical relationship is most easily accomplished by developing a third order or higher order polynomial function using ordinary least-squares regression. The bathymetry dialog box allows the user to specify the coefficients of a best-fit polynomial for the surface area/reservoir storage relationship. For the hypothetical reservoir, specify a zero-order polynomial with a surface area of 0.063 square miles (set the constant to 0.063) then click *Ok*.

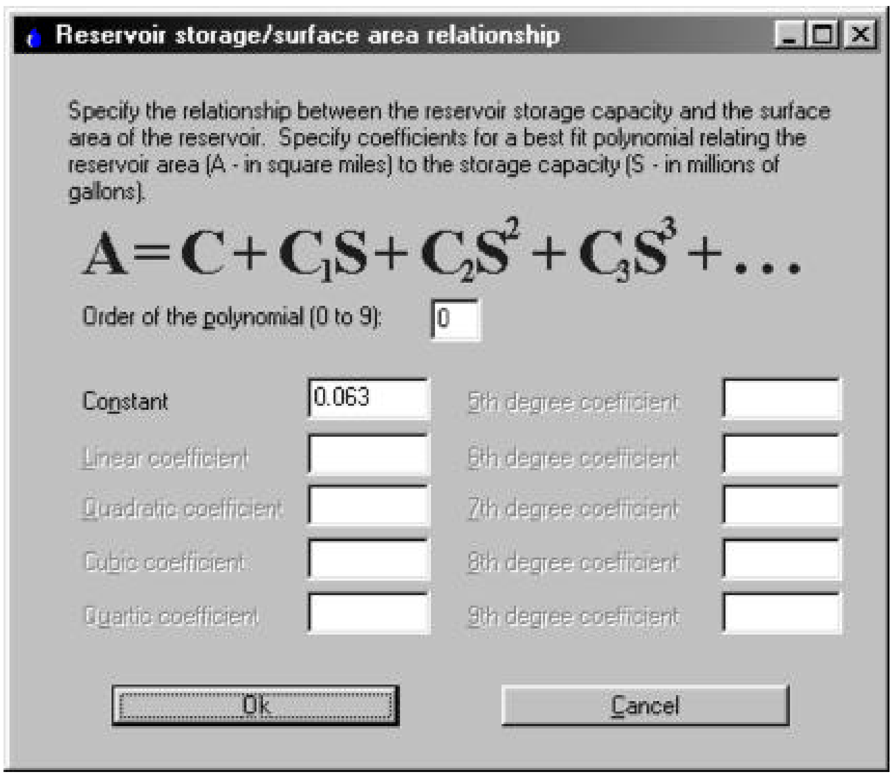

Figure 3.6 Bathymetry dialog box

Next, specify the evaporation rate from the reservoir by selecting the *Data|Evaporation rates* menu item. This will bring up the evaporation rates dialog box (Figure 3.7). If site-specific monthly evaporation rates are known for a reservoir, the user can select the *Specify monthly evaporation rates* radio button and specify evaporation rates (in inches) for each month then click *Ok*. For the hypothetical reservoir, allow the FYE to calculate evaporation rates from the meteorological data. Select the *Estimate evaporation from meteorological data* radio button, then click *Ok*. A second dialog box will appear (Figure 3.8) requesting the longitude and elevation of the reservoir. Specify the longitude to be 72.484E W and the elevation to be 470 feet above sea level, then click *Ok*.

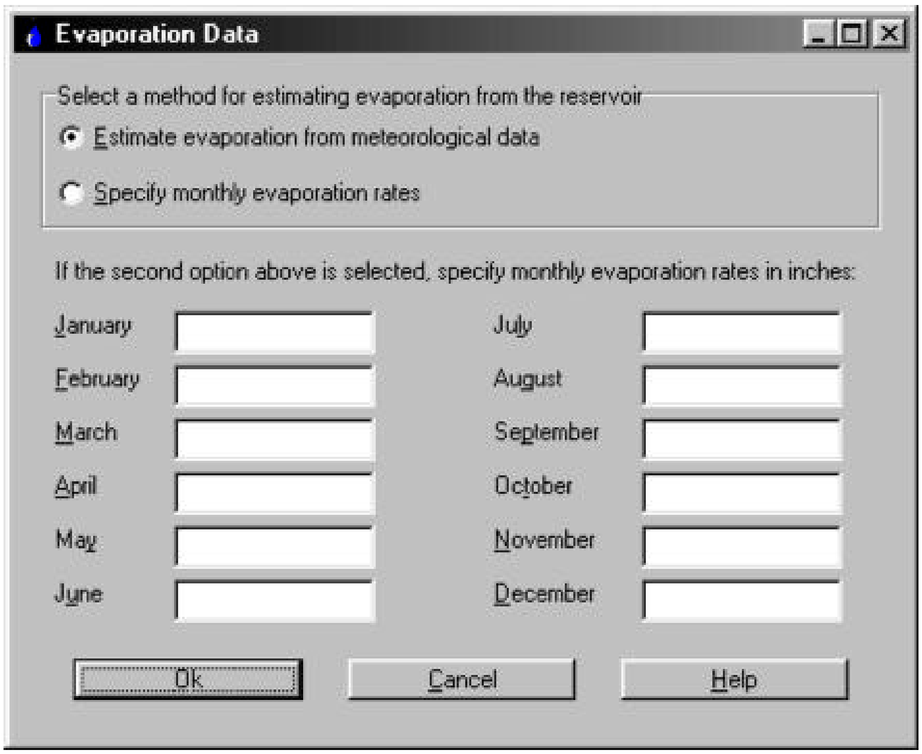

Figure 3.7 Evaporation data dialog box

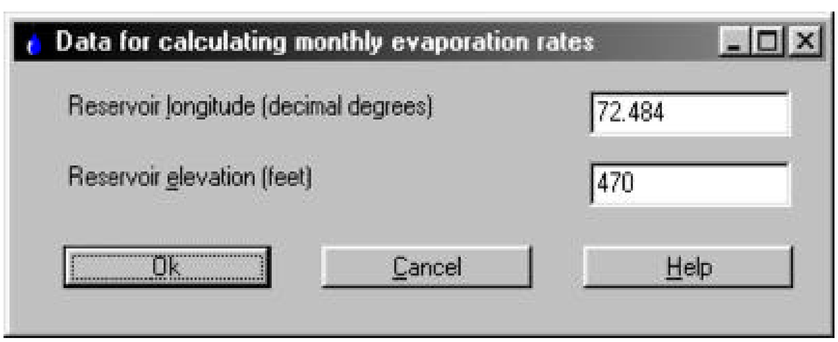

Figure 3.8 Second evaporation dialog box

Peak use factors adjust for seasonal variations in water use. Generally, water use is higher in the summer months than in the winter. Select the *Data|Peak use factors* option from the menu, and enter the following peak use factors: 1.08 in January, 1.03 in February, 1.20 in March, 1.15 in April, 1.19 in May, 1.10 in June, 1.19 in July, 1.13 in August, 0.85 in September, 0.56 in October, 0.54 in November, and 0.99 in December. Then click *Ok*. The peak use factor dialog box is shown in Figure 3.9.

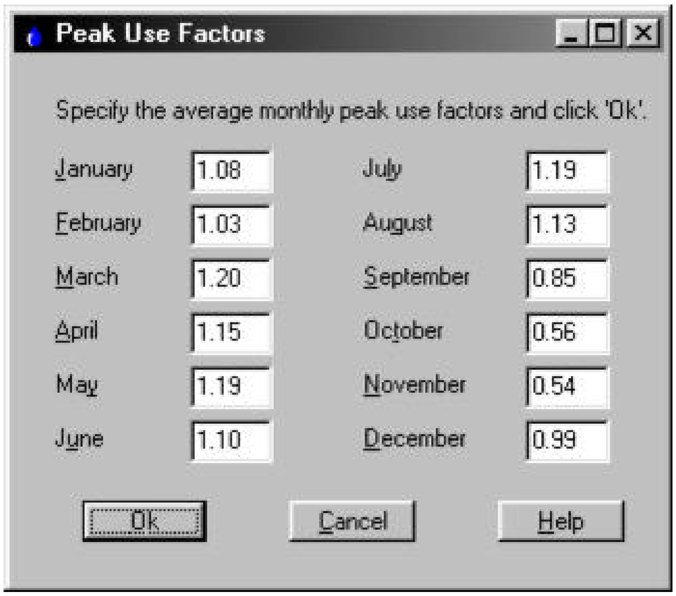

Figure 3.9 Peak use factors dialog box

Finally, specify withdrawals by other users. Assume there are no withdrawals by other users from the hypothetical reservoir. Select the *Data|Withdrawals by other users* option and accept the default of zero withdrawals in every month by clicking *Ok*. Figure 3.10 shows the dialog box used to specify withdrawals by other users.

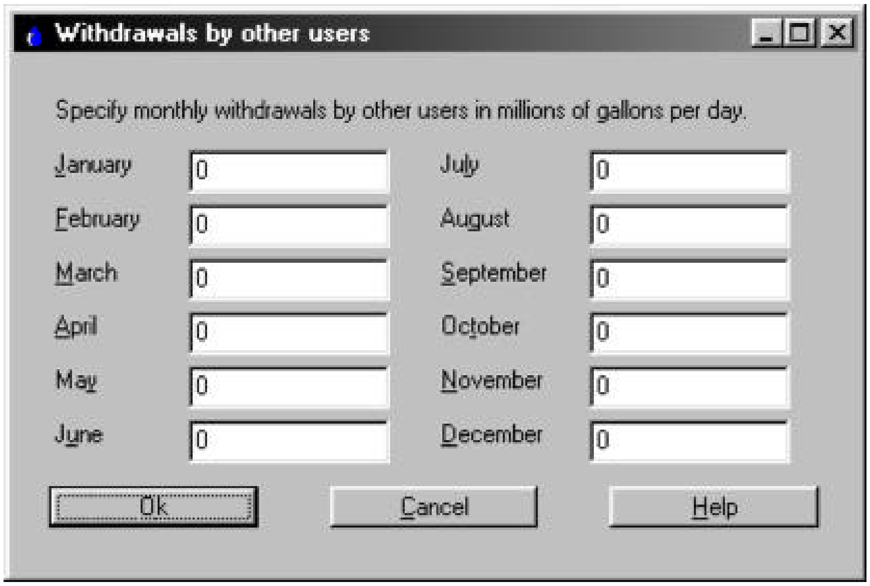

Figure 3.10 Withdrawals by other users dialog box

After all the above data have been entered, one can begin the analysis of the data. Read through the information presented in the main window of the FYE to ensure that all data have been entered. This screen should display the name of the meteorological station and stream gauge. Additionally, this window should indicate that reservoir characteristics, bathymetry data, withdrawals by other users, peak use factors, and evaporation rates are complete. Figure 3.11 shows the main window as it should look at this stage of the analysis. If any of these data have not been entered, go back and enter the missing data now.

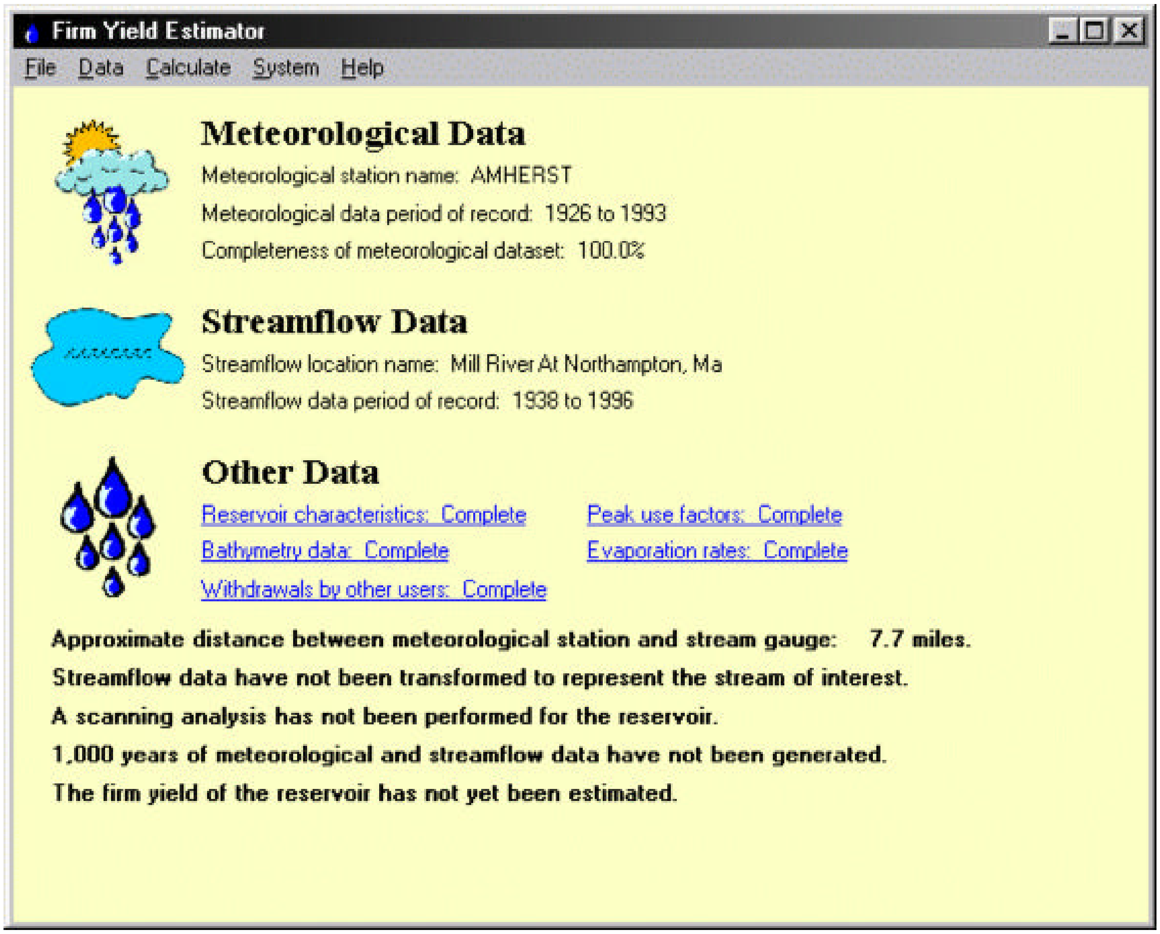

Figure 3.11 Main window of the Firm Yield Estimator after entering data

The first calculation that needs to be performed is the calculation of inflows to the surface water reservoir. To do this, select the *Calculate|Transform USGS data* option. A few additional pieces of information are necessary prior to calculating inflows to the reservoir from existing streamflow and meteorological data. Specify the average watershed elevation to be 850 feet, the mean channel slope to be 182 ft/mile, and the maximum soil retention to be 6.39 inches in the stream gauge transform dialog box (Figure 3.12). Allow the FYE to calculate the average annual precipitation and snowfall for the reservoir from the meteorological data and click *Ok*. The FYE will display a warning message indicating that streamflow data in the month of November 1938 are incomplete. This is expected because this is the first month in which streamflow data were collected at this particular stream gauge, and the first date on which data were collected was November 18, 1938. Click *Ok* to dismiss the error message. The bottom of the main window will now display a message informing the user that the streamflow data have been transformed.

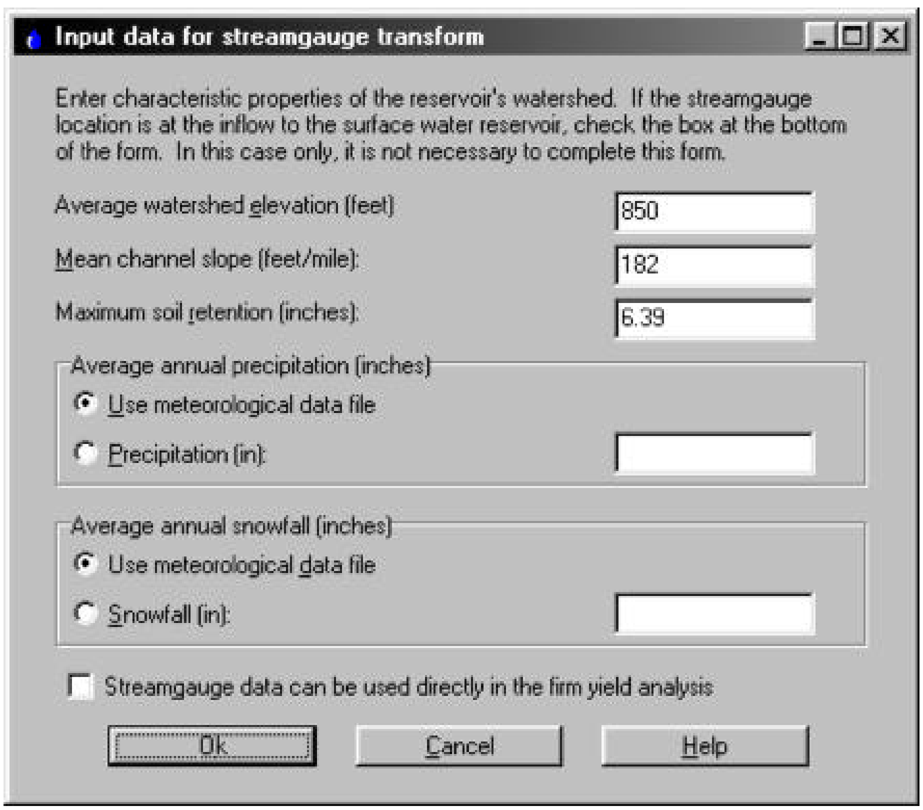

Figure 3.12 Dialog box for streamflow transform

After the streamflow data have been transformed, the *Perform scanning analysis* option will be accessible on the *Calculate* menu. Select this option to perform a scanning analysis for the reservoir. The FYE will display the results of the scanning analysis graphically as shown in Figure 3.13. For the hypothetical reservoir, the scanning yield of the reservoir is 3.188 million gallons per day. More importantly, the scanning analysis shows that the reservoir does not refill during only 3.7% of the years in the period of record. If the reservoir does not refill during 15% or more of the period of record, it is necessary to generate a 1,000-year sequence of streamflow and meteorological data prior to performing the full firm yield analysis. Click the *Close* button at the bottom of the graph to close the graph window and continue with the analysis.

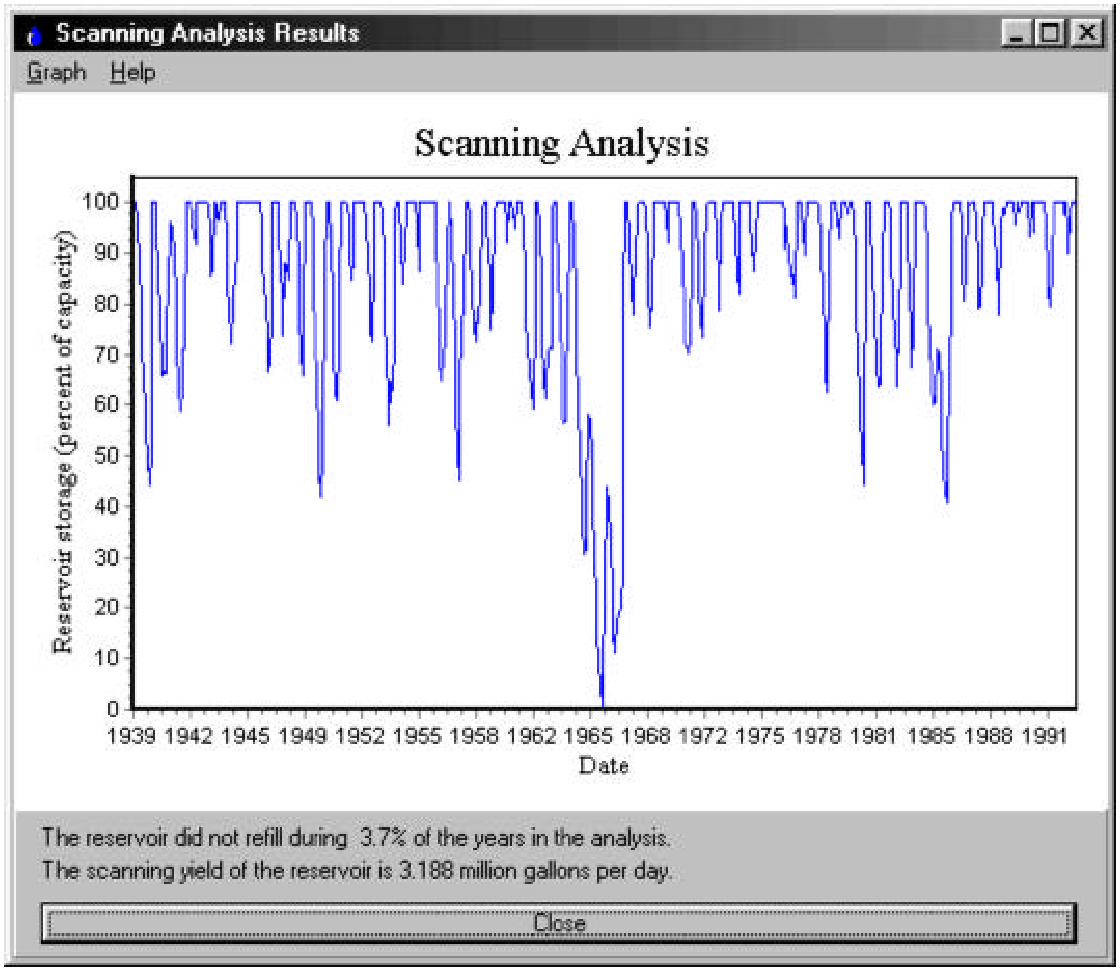

Figure 3.13 Results of the scanning analysis

Although it is unnecessary to do so for the hypothetical reservoir, the next step in a typical firm yield analysis is to generate a 1,000-year sequence of data. For the sake of practice, select *Calculate|Generate meteorological data*. The FYE gives the user the option of generating the 1,000-year sequence from the entire period for which streamflow and meteorological data are available or selecting a subset of the period to use when generating data (see Figure 3.14). Select the radio button labeled *Use the entire period for which data are available* and click *Ok*. The FYE has now generated 1,000 years of meteorological data, as indicated at the bottom of the main window.

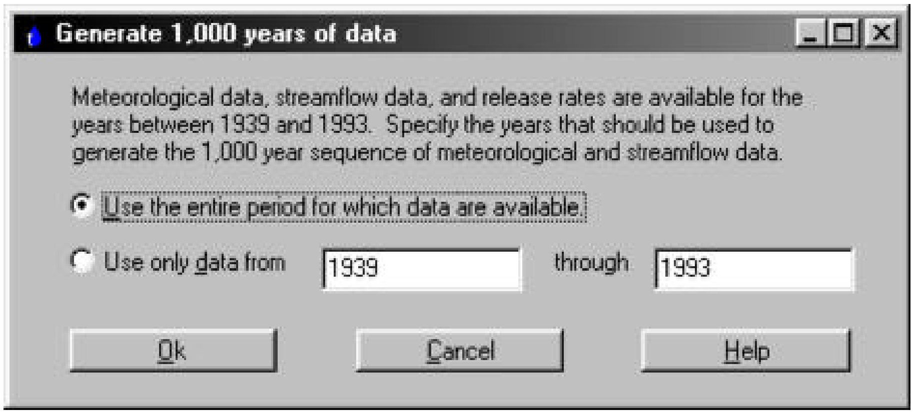

Figure 3.14 Dialog box for the generation of the 1,000-year data sequence

The final step is the actual estimation of the firm yield for the surface water reservoir. Select the *Calculate|Estimate firm yield* option. The FYE gives the user the option of performing the firm yield calculation based on actual meteorological and streamflow data, or the generated 1,000-year sequence of data (see Figure 3.15). Because the scanning analysis indicated that using the 1,000-year sequence of data is unnecessary for the hypothetical reservoir, select the button labeled *Actual meteorological and streamflow data* and click *Ok*. As it did for the scanning analysis, the FYE will display a graph of the results of the firm yield analysis (Figure 3.16). The firm yield of the hypothetical reservoir is 3.322 million gallons per day. Click *Close* to close the graph and return to the main window of the program.

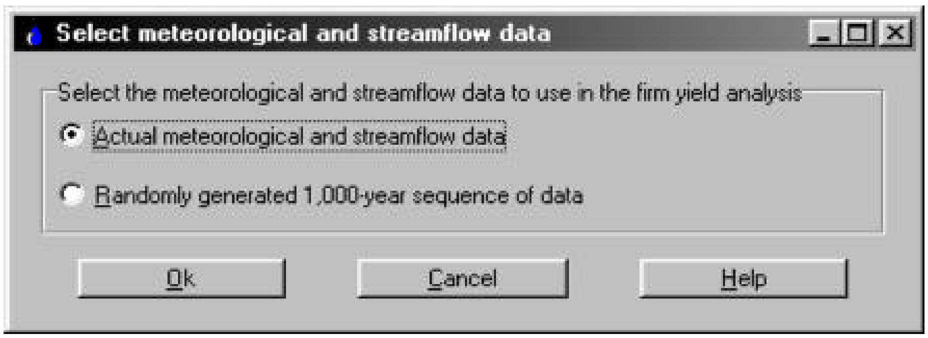

Figure 3.15 Dialog box for selecting data in the firm yield analysis

If *Actual meteorological and streamflow data* is selected, a second dialog box appears asking the user to specify the years to use in the analysis. This option allows the user to specify a period less than the period of overlap for the meteorological and streamflow data. For example, the user could exclude the 1960's drought of record (after receiving DEP approval) and instead use only the period from 1970 through 1993 to estimate the firm yield. Simply accept the maximum range (1939 through 1993) by pressing the *Ok* button.

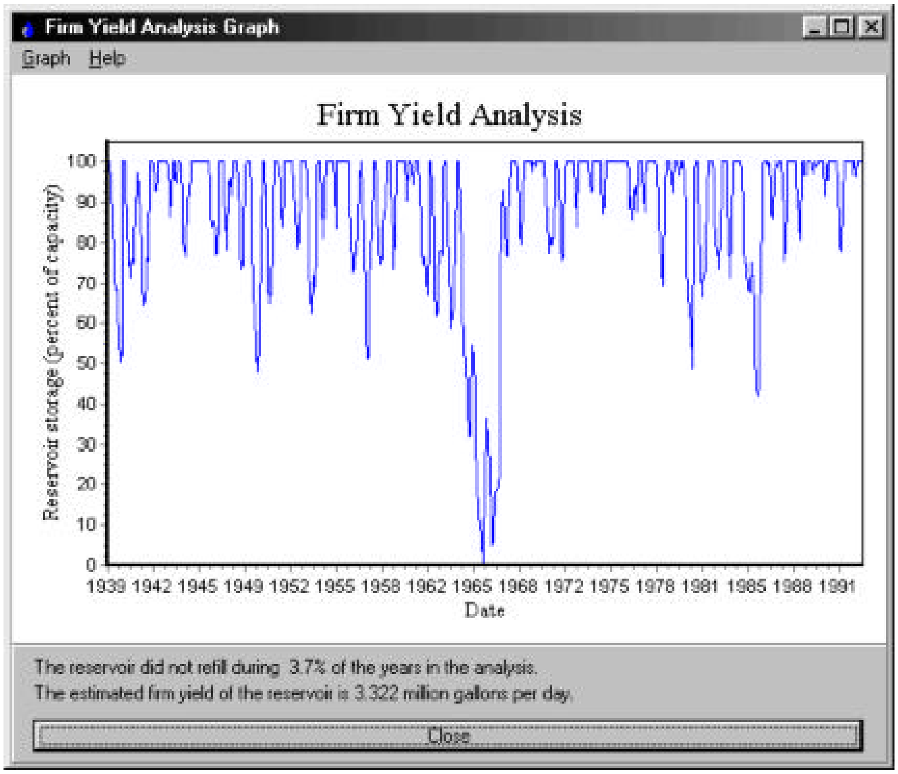

Figure 3.16 Graph of the results of the firm yield analysis

The firm yield analysis of the hypothetical reservoir is now complete. To save the analysis, select *Save* from the *File* menu. Select the directory in which to save the file and specify a filename. Then click on the *Save* button in the dialog box. To close the FYE, select *Exit* from the *File* menu or click on the x in the top right corner of the main program window.

4 Database descriptions

Two databases are included on the CD-ROM provided with the Firm Yield Estimator, one containing meteorological data and one containing streamflow data. The meteorological database contains maximum and minimum temperature, precipitation, and snowfall data for meteorological stations in Massachusetts and in neighboring states at stations within about 15 miles of the Massachusetts border. The streamflow database contains daily streamflow measurements at USGS stream gauge locations in Massachusetts and stream gauge locations in neighboring states but near the Massachusetts border. The sections below describe the data provided in these two databases in detail. CDW Consultants, Inc. provided assistance in compiling the databases.

4.1 Meteorological database

The meteorological data provided with the Firm Yield Estimator were obtained in electronic format on CD-ROM's from the National Oceanic and Atmospheric Administration (NOAA, 1995a; NOAA, 1995b). The NOAA data include daily measurements of maximum temperature, minimum temperature, precipitation, and snowfall as well as other parameters for some stations, such as soil temperatures and evaporation. The NOAA data were preprocessed using the Firm Yield Estimator to obtain the monthly meteorological parameters required to estimate the yield of a surface water reservoir per DEP's guidance (DEP, 1996). These preprocessed data files are the files that are included in the Firm Yield Estimator's meteorological database.

The meteorological stations that are included in the database are summarized in Tables 4.1 and 4.2 below. Figure 4.1 is a map showing the locations of all the meteorological stations in the database. A large number of meteorological stations for which NOAA provides data include only a few years of data or are missing data that are necessary to perform the firm yield analysis (such as precipitation or temperature data). The database includes all stations in Massachusetts for which the necessary parameters were provided for the minimum time period required by DEP, April 1960 through March 1990. The database also includes stations in bordering states that are near the Massachusetts border. This includes stations in Vermont and New Hampshire that are south of 43EN latitude, stations in Connecticut and Rhode Island that are north of 41E45' N latitude, and stations in New York that are east of 74EW longitude and between 41E45' N and 43EN latitude. Meteorological data for Hartford's Brainard Field and Providence's T.F. Green State Airport are also included because they represent large, relatively complete data sets that are just south of the 41E45' N latitude cutoff.

Table 4.1 presents each meteorological station by name and station number, the dates for which data are available, and the latitude and longitude of the station. Table 4.2 provides a summary of the completeness of the monthly meteorological data for each station.

The filenames for the meteorological data files consist of the station number with the extension *.met*. Hence, the filename for Boston's Logan International Airport is *190770.met*. The format of the meteorological data files is relatively simple. The first line of the file contains an integer specifying the number of months included in the datafile. The second line of the file is the station number and the third line is the station name. The fourth and fifth lines are the latitude and longitude of the meteorological station. All subsequent lines are meteorological data, one line per month. Each line consists of (from left to right) the month (an integer between 1 and 12), the year, the maximum monthly temperature, the minimum monthly temperature, the total monthly snowfall, and the total monthly precipitation. If any data are missing for a given month, an error code of -99999 is reported instead of the missing parameter(s). The two pages of the data file for Boston's Logan International Airport (filename *190770.met*) are shown in Appendix A.

4.2 Streamflow database

The streamflow data provided with the Firm Yield Estimator were downloaded from the United States Geological Survey (USGS) website at http://water.usgs.gov. Daily streamflow data were downloaded for all stream gauges in Massachusetts for which data were available for the period from April 1, 1960 through March 30, 1990. Additionally, data were downloaded for all stream gauges in bordering states within about 15 miles of the Massachusetts border.

Figure 4.2 and Table 4.3 present the stream gauge locations that are included in the Firm Yield Estimator's database. From left to right, the table includes the name of the stream gauge, the station number for the stream gauge, the first and last dates for which streamflow measurements are available, and the latitude and longitude of the stream gauge location.

The filenames for the streamflow data files consist of the station number for the stream gauge plus the extension *.txt*. Hence, the filename for data collected from the Shawsheen River near Wilmington, Massachusetts (station number 01100600) is *01100600.txt*. Approximately the first 35 lines of each streamflow data file are a header for the file. Each of these lines begins with the "#" character. The header for each file contains descriptive parameters for the stream gauge (location, latitude, longitude, drainage area, etc.) as well as a description of the format for the rest of the file. After the header lines, the first line of the file contains the column headings "Date", "Discharge", and "Flags". The next line is a row of tab-delimited data type codes that describe a 10-character-wide date (10d), an 8-character-wide numeric value for discharge (8n), and a 2-character-wide string as a qualifying flag (2s). All following lines are tab-delimited data values of date and discharge. The first two pages of the data file for the Shawsheen River near Wilmington, Massachusetts (filename *01100600.txt*) are shown in Appendix B.

Almost all stream gauges in the vicinity of Massachusetts are regulated to some extent upstream of the stream gauge. Table 4.4 summarizes the flow rate at each location in the database. Table 4.5 gives a brief description of the extent to which each station in the streamflow database is regulated. DEP requires that the analyst employ data from the nearest U.S. Geological Survey streamgauge to the reservoir that is sufficiently unregulated and includes the period from April 1, 1960 to March 31, 1990. Table 4.5 is intended to give some guidance as to the extent of regulation at each stream gauge; however, DEP must be consulted about the proposed streamgauge before beginning the analysis.

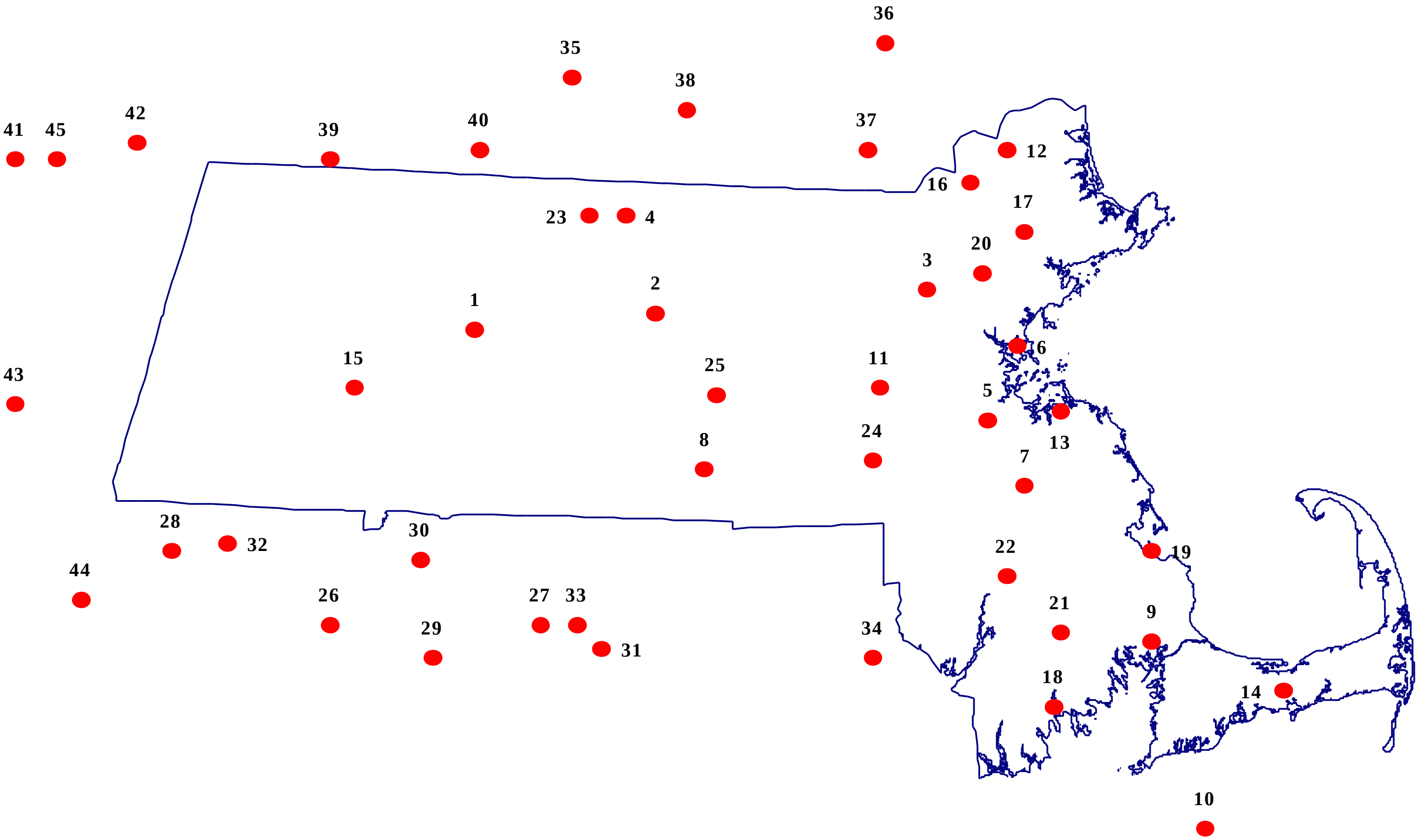

Figure 4.1 Map of meteorological stations in the database. The numbers correspond to the Map ID's in Table 4.1.

Table 4.1 Meteorological stations reporting data between 1960 and 1990

Station Name	Map ID	Station Number	Dates	Latitude (North)	Longitude (West)
Massachusetts					
Amherst	1	190120	January 1926 to December 1993	42°24'	72°32'
Barre Falls/Dam	2	190408	February 1959 to December 1993	42°26'	72°02'
Bedford	3	190535	May 1957 to December 1993	42°29'	71°17'
Birch Hill/Dam	4	190666	June 1948 to December 1993	42°38'	72°07'
Milton/Blue Hill Observatory	5	190736	January 1926 to December 1993	42°13'	71°07'
Boston/Logan International Airport	6	190770	January 1920 to December 1993	42°22'	71°02'
Brockton	7	190860	June 1948 to December 1993	42°05'	71°01'
Buffumville/Lake	8	190998	May 1959 to December 1993	42°07'	71°54'
East Wareham	9	192451	January 1926 to December 1993	41°46'	70°40'
Edgartown	10	192501	June 1948 to December 1993	41°23'	70°31'
Framingham	11	192975	June 1948 to November 1989	42°17'	71°25'
Haverhill	12	193505	June 1948 to December 1993	42°46'	71°04'
Hingham	13	193624	September 1960 to December 1993	42°14'	70°55'
Hyannis	14	193821	April 1926 to December 1993	41°40'	70°18'
Knightville/Dam	15	193985	June 1948 to December 1993	42°17'	72°52'
Lawrence	16	194105	January 1926 to December 1993	42°42'	71°10'
Middleton	17	194744	June 1948 to December 1993	42°36'	71°01'
New Bedford	18	195246	June 1948 to December 1993	41°38'	70°56'
Plymouth-Kingston	19	196486	June 1948 to December 1993	41°57'	70°40'
Reading	20	196783	January 1960 to December 1993	42°31'	71°08'
Rochester	21	196938	November 1951 to December 1993	41°47'	70°55'
Taunton	22	198367	June 1948 to December 1993	41°54'	71°04'
Tully/Lake	23	198573	July 1949 to December 1993	42°38'	72°13'
West Medway	24	199316	January 1957 to December 1993	42°08'	71°26'
Worcester/Municipal Airport	25	199923	June 1948 to December 1993	42°16'	71°52'
Connecticut					
Burlington	26	60973	January 1937 to December 1993	41°48'	72°56'
Coventry	27	61689	April 1957 to September 1993	41°48'	72°21'
Falls Village	28	62658	June 1948 to December 1993	41°57'	73°22'
Hartford/Brainard Field	29	63451	January 1920 to December 1993	41°44'	72°39'
Hartford/Bradley International Airport	30	63456	August 1954 to December 1993	41°56'	72°41'
Mansfield/Hollow Lake	31	64488	May 1952 to December 1993	41°45'	72°11'
Norfolk	32	65445	September 1942 to December 1993	41°58'	73°13'
Storrs	33	68138	June 1888 to December 1993	41°48'	72°15'
Rhode Island					
Providence/T.F. Green State Airport	34	376698	June 1948 to December 1993	41°44'	71°26'
New Hampshire					
Keene	35	274399	January 1926 to December 1993	42°55'	72°16'
Massabesic/Lake	36	275211	June 1948 to December 1993	42°59'	71°24'
Nashua	37	275712	June 1948 to December 1993	42°46'	71°27'
Peterboro	38	276697	June 1948 to December 1993	42°51'	71°57'
Vermont					
Readsboro	39	436761	June 1948 to December 1993	42°45'	72°56'
Vernon	40	438600	June 1948 to December 1993	42°46'	72°31'
New York					
Albany/County Airport	41	300042	June 1938 to December 1993	42°45'	73°48'
Grafton	42	303360	September 1950 to December 1993	42°47'	73°28'
Hudson/Correctional Facility	43	304025	March 1957 to December 1993	42°15'	73°48'
Millbrook	44	305334	May 1948 to December 1993	41°51'	73°37'
Troy/Lock and Dam	45	308600	November 1932 to December 1993	42°45'	73°41'

Table 4.2 Missing meteorological data summary

Name	Total months	Number of months with missing data				Percent of months with missing data			
		Max. temp.	Min. temp.	Snow	Precip.	Max. temp.	Min. temp.	Snow	Precip.
Massachusetts									
Amherst	816	2	2	16	2	0.2%	0.2%	2.0%	0.2%
Barre Falls/Dam	419	1	1	2	0	0.2%	0.2%	0.5%	0.0%
Bedford	440	3	3	4	3	0.7%	0.7%	0.9%	0.7%
Birch Hill/Dam	547	2	3	2	0	0.4%	0.5%	0.4%	0.0%
Milton/Blue Hill Observatory	816	6	6	134	8	0.7%	0.7%	16.4%	1.0%
Boston/Logan International Airport	888	0	0	13	0	0.0%	0.0%	1.5%	0.0%
Brockton	547	36	36	87	3	6.6%	6.6%	15.9%	0.5%
Buffumville/Lake	416	0	0	14	0	0.0%	0.0%	3.4%	0.0%
East Wareham	816	7	7	37	1	0.9%	0.9%	4.5%	0.1%
Edgartown	547	3	3	98	3	0.5%	0.5%	17.9%	0.5%
Framingham	498	15	15	22	14	3.0%	3.0%	4.4%	2.8%
Haverhill	547	12	12	10	8	2.2%	2.2%	1.8%	1.5%
Hingham	400	0	0	0	0	0.0%	0.0%	0.0%	0.0%
Hyannis	813	94	94	289	70	11.6%	11.6%	35.5%	8.6%
Knightville/Dam	547	3	3	12	1	0.5%	0.5%	2.2%	0.2%
Lawrence	816	2	2	14	6	0.2%	0.2%	1.7%	0.7%
Middleton	547	1	1	22	1	0.2%	0.2%	4.0%	0.2%
New Bedford	547	3	3	5	2	0.5%	0.5%	0.9%	0.4%
Plymouth-Kingston	547	1	1	24	1	0.2%	0.2%	4.4%	0.2%
Reading	408	0	0	0	0	0.0%	0.0%	0.0%	0.0%
Rochester	506	2	2	61	2	0.4%	0.4%	12.1%	0.4%
Taunton	547	0	1	11	0	0.0%	0.2%	2.0%	0.0%
Tully/Lake	534	6	6	2	1	1.1%	1.1%	0.4%	0.2%
West Medway	444	1	1	1	1	0.2%	0.2%	0.2%	0.2%
Worcester/Municipal Airport	547	0	0	0	0	0.0%	0.0%	0.0%	0.0%
Connecticut									
Burlington	684	305	305	187	17	44.6%	44.6%	27.3%	2.5%
Coventry	438	29	32	41	28	6.6%	7.3%	9.4%	6.4%
Falls Village	547	0	0	54	0	0.0%	0.0%	9.9%	0.0%
Hartford/Brainard Field	888	8	8	161	8	0.9%	0.9%	18.1%	0.9%
Hartford/Bradley International Airport	473	0	0	0	0	0.0%	0.0%	0.0%	0.0%
Mansfield/Hollow Lake	500	1	1	8	1	0.2%	0.2%	1.6%	0.2%
Norfolk	616	1	1	1	1	0.2%	0.2%	0.2%	0.2%
Storrs	1267	34	33	193	33	2.7%	2.6%	15.2%	2.6%
Rhode Island									
Providence/T.F. Green State Airport	547	7	7	7	1	1.3%	1.3%	1.3%	0.2%
New Hampshire									
Keene	816	3	3	127	2	0.4%	0.4%	15.6%	0.2%
Massabesic/Lake	547	17	16	123	15	3.1%	2.9%	22.5%	2.7%
Nashua	547	2	3	25	2	0.4%	0.5%	4.6%	0.4%
Peterboro	547	30	30	31	31	5.5%	5.5%	5.7%	5.7%
Vermont									
Readsboro	547	34	34	3	2	6.2%	6.2%	0.5%	0.4%
Vernon	547	33	33	9	1	6.0%	6.0%	1.6%	0.2%
New York									
Albany/County Airport	667	0	0	0	0	0.0%	0.0%	0.0%	0.0%
Grafton	520	5	5	14	5	1.0%	1.0%	2.7%	1.0%
Hudson/Correctional Facility	442	15	16	64	20	3.4%	3.6%	14.5%	4.5%
Millbrook	548	10	11	33	15	1.8%	2.0%	6.0%	2.7%
Troy/Lock and Dam	734	287	287	310	288	39.1%	39.1%	42.2%	39.2%

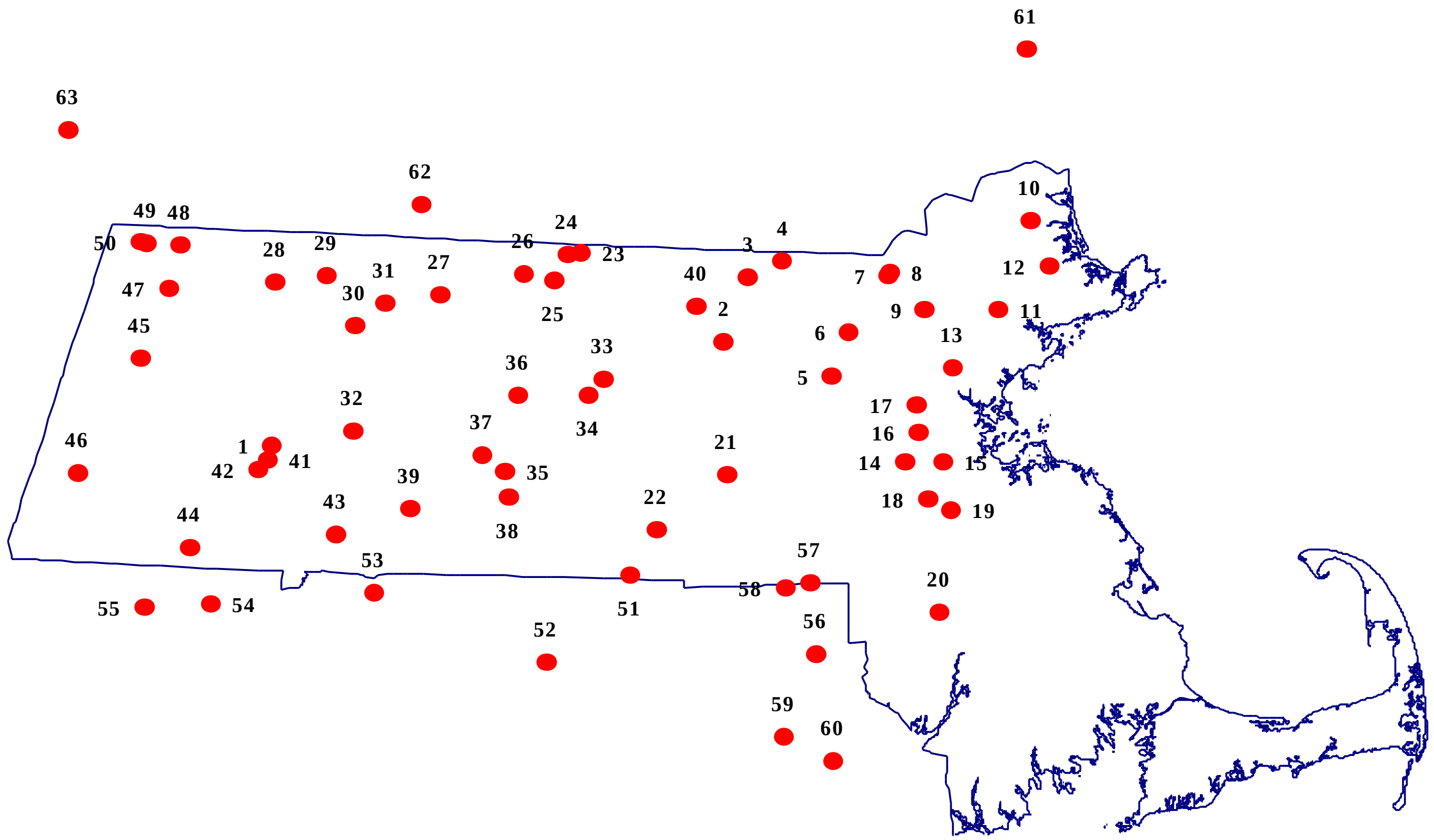

Figure 4.2 Map of streamflow stations in the database. The numbers correspond to the Map ID's in Table 4.3.

Table 4.3 USGS stream discharge data

Station Name	Map ID	Station Number	First Date	Last Date	Latitude	Longitude
Massachusetts						
Westfield River At Knightville, MA	1	01179500	08/26/09	09/30/90	42°17'16"	72°51'53"
North Nashua River Near Leominster, MA	2	01094500	09/17/35	09/30/92	42°30'06"	71°43'23"
Squannacook River Near West Groton, MA	3	01096000	10/01/49	09/30/92	42°38'03"	71°39'30"
Nashua River At East Pepperell, MA	4	01096500	10/01/35	09/30/96	42°40'03"	71°34'32"
Assabet River At Maynard, MA	5	01097000	07/11/41	09/30/96	42°25'55"	71°27'01"
Nashoba Brook Near Acton, MA	6	01097300	07/26/63	09/30/96	42°31'19"	71°24'15"
Concord R Below R Meadow Brook, At Lowell, MA	7	01099500	12/16/36	09/30/96	42°38'12"	71°18'09"
Merrimack River Bl Concord River At Lowell, MA	8	01100000	06/01/23	09/30/96	42°38'45"	71°17'56"
Shawsheen River Near Wilmington, MA	9	01100600	11/21/63	09/30/96	42°34'05"	71°12'55"
Parker River At Byfield, MA	10	01101000	10/26/45	09/30/96	42°45'10"	70°56'46"
Ipswich River At South Middleton, MA	11	01101500	06/01/38	09/30/96	42°34'10"	71°01'39"
Ipswich River Near Ipswich, MA	12	01102000	06/17/30	09/30/96	42°39'35"	70°53'39"
Aberjona River At Winchester, MA	13	01102500	04/16/39	09/30/96	42°26'50"	71°08'22"
Charles River At Dover, MA	14	01103500	10/01/37	09/30/96	42°15'22"	71°15'38"
Mother Brook At Dedham, MA	15	01104000	10/01/31	09/30/96	42°15'18"	71°09'53"
Charles River At Wellesley, MA	16	01104200	08/26/59	09/30/96	42°18'59"	71°13'42"
Charles River At Waltham, MA	17	01104500	08/04/31	09/30/96	42°22'20"	71°14'03"
Neponset River At Norwood, MA	18	01105000	10/01/39	09/30/96	42°10'39"	71°12'05"
East Branch Neponset River At Canton, MA	19	01105500	10/01/52	09/30/96	42°09'16"	71°08'47"
Wading River Near Norton, MA	20	01109000	06/01/25	09/30/96	41°56'51"	71°10'38"
Quinsigamond River At North Grafton, MA	21	01110000	10/01/39	09/30/96	42°13'49"	71°42'41"
Little River Near Oxford, MA	22	01124500	07/27/39	09/30/90	42°06'57"	71°53'26"
Millers River Near Winchendon, MA	23	01162000	06/05/16	09/30/96	42°41'03"	72°05'02"
Priest Brook Near Winchendon, MA	24	01162500	10/01/36	09/30/96	42°40'57"	72°06'56"
Millers River At South Royalston, MA	25	01164000	07/27/39	09/30/90	42°37'47"	72°09'03"
East Branch Tully River Near Athol, MA	26	01165000	06/13/16	09/30/90	42°38'32"	72°13'34"
Millers River At Erving, MA	27	01166500	07/01/15	09/30/96	42°35'51"	72°26'19"
Deerfield River At Charlemont, MA	28	01168500	06/19/13	09/30/96	42°37'33"	72°51'20"
North River At Shattuckville, MA	29	01169000	12/13/39	09/30/96	42°38'18"	72°43'32"
Deerfield River Near West Deerfield, MA	30	01170000	10/01/40	09/30/96	42°32'09"	72°39'14"
Connecticut River At Montague City, MA	31	01170500	03/31/04	09/30/96	42°34'48"	72°34'30"
Mill River At Northampton, MA	32	01171500	11/18/38	09/30/96	42°19'05"	72°39'21"
Ware River Near Barre, MA	33	01172500	07/27/46	09/30/96	42°25'35"	72°01'30"
Ware River At Intake Works Near Barre, MA	34	01173000	01/30/28	09/30/96	42°23'26"	72°03'39"
Ware River At Gibbs Crossing, MA	35	01173500	08/20/12	09/30/96	42°14'10"	72°16'23"
East Branch Swift River Near Hardwick, MA	36	01174500	01/01/37	09/30/96	42°23'36"	72°14'21"
Swift River At West Ware, MA	37	01175500	10/01/12	09/30/96	42°16'04"	72°19'59"
Quaboag River At West Brimfield, MA	38	01176000	08/19/12	09/30/96	42°10'56"	72°15'51"
Chicopee River At Indian Orchard, MA	39	01177000	08/05/28	09/30/97	42°09'38"	72°30'52"
North Nashua River At Fitchburg, MA	40	01094400	10/01/72	09/30/96	42°34'34"	71°47'19"
Middle B Westfield River At Goss Heights, MA	41	01180500	07/14/10	09/30/90	42°15'31"	72°52'23"
West Branch Westfield River At Huntington, MA	42	01181000	09/01/35	09/30/97	42°14'14"	72°53'46"
Westfield River Near Westfield, MA	43	01183500	06/27/14	09/30/97	42°06'24"	72°41'58"
West Branch Farmington River Near New Boston, MA	44	01185500	05/27/13	09/30/97	42°04'45"	73°04'24"
East Branch Housatonic River At Coltsville, MA	45	01197000	03/08/36	09/30/97	42°28'10"	73°11'49"
Housatonic River Near Great Barrington, MA	46	01197500	05/17/13	09/30/97	42°13'55"	73°21'19"
Hoosic River At Adams, MA	47	01331500	10/01/31	09/30/97	42°36'40"	73°07'28"
North Branch Hoosic River At North Adams, MA	48	01332000	06/22/31	09/30/90	42°42'08"	73°05'37"
Hoosic River Near Williamstown, MA	49	01332500	07/19/40	09/30/97	42°42'21"	73°10'50"
Green River At Williamstown, MA	50	01333000	09/20/49	09/30/97	42°42'32"	73°11'50"
Connecticut						
Quinebaug R At Quinebaug, CT	51	01124000	10/01/31	09/30/97	42°01'20"	71°57'22"

Table 4.3 USGS stream discharge data

Station Name	Map ID	Station Number	First Date	Last Date	Latitude	Longitude
Mount Hope R Nr Warrenville, CT	52	01121000	10/01/40	09/30/97	41°50'37"	72°10'10"
Connecticut R At Thompsonville, CT	53	01184000	08/01/28	09/30/97	41°59'14"	72°36'21"
West Branch Farmington R At Riverton, CT	54	01186000	10/01/55	09/30/97	41°57'46"	73°01'05"
Housatonic R At Falls Village, CT	55	01199000	10/01/12	09/30/97	41°57'26"	73°22'11"
Rhode Island						
Woonasquatucket River At Centerdale, RI	56	01114500	07/09/41	09/30/97	41°51'32"	71°29'16"
Blackstone River At Woonsocket, RI	57	01112500	02/22/29	09/30/97	42°00'22"	71°30'13"
Branch River At Forestdale, RI	58	01111500	01/24/40	09/30/97	41°59'47"	71°33'47"
South Branch Pawtuxet River At Washington, RI	59	01116000	10/01/40	09/30/97	41°41'24"	71°33'59"
Hunt River Near East Greenwich, RI	60	01117000	08/24/40	09/30/97	41°38'28"	71°26'45"
New Hampshire						
Lamprey River Near Newmarket, NH	61	01073500	07/24/34	09/30/97	43°06'09"	70°57'11"
Ashuelot River At Hinsdale, NH	62	01161000	07/11/14	09/30/97	42°47'07"	72°29'12"
New York						
Hoosic River Near Eagle Bridge, NY	63	01334500	07/25/23	09/30/97	42°56'19"	73°22'39"

Table 4.4 Average flow of streams in the streamflow database

Station Name	Average flow (ft^3/s)
Massachusetts	
Aberjona River At Winchester, Ma	28.9
Assabet River At Maynard, Ma	188.1
Charles River At Dover, Ma	304
Charles River At Waltham, Ma	305.3
Charles River At Wellesley, Ma	282.9
Chicopee River At Indian Orchard, Ma	916.9
Concord R Below R Meadow Brook, At Lowell, Ma	645.6
Connecticut River At Montague City, Ma	13920.9
Deerfield River At Charlemont, Ma	897.5
Deerfield River Near West Deerfield, Ma	1307.9
East Branch Housatonic River At Coltsville, Ma	107.2
East Branch Neponset River At Canton, Ma	50.6
East Branch Swift River Near Hardwick, Ma	71.5
East Branch Tully River Near Athol, Ma	81.8
Green River At Williamstown, Ma	82.6
Hoosic River At Adams, Ma	90.2
Hoosic River Near Williamstown, Ma	272.9
Housatonic River Near Great Barrington, Ma	526.5
Ipswich River At South Middleton, Ma	63.5
Ipswich River Near Ipswich, Ma	186.2
Little River Near Oxford, Ma	49.5
Merrimack River Bl Concord River At Lowell, Ma	7641.1
Middle B Westfield River At Goss Heights, Ma	105
Mill River At Northampton, Ma	97.8
Millers River At Erving, Ma	637
Millers River At South Royalston, Ma	327.6
Millers River Near Winchendon, Ma	144.7
Mother Brook At Dedham, Ma	76.3
Nashoba Brook Near Acton, Ma	20.5
Nashua River At East Pepperell, Ma	580.2
Neponset River At Norwood, Ma	55.1
North Branch Hoosic River At North Adams, Ma	96.5
North Nashua River At Fitchburg, Ma	328.9
North Nashua River Near Leominster, Ma	197.3
North River At Shattuckville, Ma	186.7
Parker River At Byfield, Ma	36.9
Priest Brook Near Winchendon, Ma	32.8
Quaboag River At West Brimfield, Ma	247.2
Quinsigamond River At North Grafton, Ma	41.3

Table 4.4 Average flow of streams in the streamflow database

Station Name	Average flow (ft^3/s)
Shawsheen River Near Wilmington, Ma	58.5
Squannacook River Near West Groton, Ma	112.1
Swift River At West Ware, Ma	164.5
Wading River Near Norton, Ma	72.7
Ware River At Gibbs Crossing, Ma	294.4
Ware River At Intake Works Near Barre, Ma	168.9
Ware River Near Barre, Ma	95
West Branch Farmington River Near New Boston, Ma	183.6
West Branch Westfield River At Huntington, Ma	192
Westfield River At Knightville, Ma	122.3
Westfield River Near Westfield, Ma	930.4
Connecticut	
Connecticut R At Thompsonville, Ct	16781.4
Housatonic R At Falls Village,Ct.	1095.2
Mount Hope R Nr Warrenville, Ct.	49.4
Quinebaug R At Quinebaug,Ct.	276.2
West Branch Farmington R At Riverton, Ct.	254.5
Rhode Island	
Blackstone River At Woonsocket, Ri	778.4
Branch River At Forestdale, Ri	175.5
Hunt River Near East Greenwich, Ri	46.5
South Branch Pawtuxet River At Washington, Ri	130.4
Woonasquatucket River At Centerdale, Ri	73.2
New Hampshire	
Ashuelot River At Hinsdale, Nh	687
Lamprey River Near Newmarket, Nh	283
New York	
Hoosic River Near Eagle Bridge Ny	958.5

Table 4.5 Regulation of streams included in the streamflow database

Station Name	Regulation
Massachusetts	
Westfield River At Knightville, Ma	Flow regulated by Knightville reservoir since 1941.
North Nashua River Near Leominster, Ma	Regulation at low flow by mills upstream. Flow includes diversion to basin for municipal supplies.
Squannacook River Near West Groton, Ma	Occasional regulation at low flow by mill upstream. Regulation greater prior to 1961.
Nashua River At East Pepperell, Ma	Includes water released while diverting flow of Nashua River for use by Boston and from the Ware River basin since 1955 for use by Fitchburg. Flow regulated by powerplant immediately upstream.
Assabet River At Maynard, Ma	Occasional diurnal fluctuation at low flow by mills upstream; greater regulation prior to 1969. Since 1962, high flow affected by retarding reservoirs and, since 1970, occasional release at low flow by these reservoirs.
Nashoba Brook Near Acton, Ma	Occasional regulation since 1967 by pond upstream.
Concord R Below R Meadow Brook, At Lowell, Ma	Low flow regulated by mills upstream. Prior to 1961, diversion upstream for use of the city of Lowell.
Merrimack River Bl Concord River At Lowell, Ma	Flow regulated by powerplants, by Franklin Falls Reservoir since 1942, and by Squam, Newfound, Winnipesaukee, Winnisquam, and other lakes and reservoirs upstream.
Shawsheen River Near Wilmington, Ma	Diversion upstream at times each year since 1973 for municipal supply of Burlington.
Parker River At Byfield, Ma	Occasional regulation by mill and ponds upstream.
Ipswich River At South Middleton, Ma	Diversions upstream for municipal supply of Reading, Lynn, and Peabody. Occasional regulation by mill upstream.
Ipswich River Near Ipswich, Ma	Diversions upstream for municipal supply of Reading, Lynn, Peabody, Danvers, Salem, and Beverly. Some regulation by reservoirs upstream.
Aberjona River At Winchester, Ma	Flow affected by diversions for industrial use and for municipal supply of Woburn and Winchester, and by wastage and leakage from Winchester North Reservoir. Some regulation by Winchester at dam 1,800 ft upstream.
Charles River At Dover, Ma	Flow affected by diversions to and from basin for municipal supplies.
Mother Brook At Dedham, Ma	Mother Brook is a diversion from Charles River to Neponset River through Dedham and Hyde Park.
Charles River At Wellesley, Ma	Flow affected by diversion to Mother Brook (station 01104000), and by diversions to and from basin for municipal supplies. Occasional regulation at dam 0.2 miles upstream and by other ponds upstream.
Charles River At Waltham, Ma	Flow affected by diversion to Mother Brook (station 01104000), diversions to and from basin for municipal supplies, and at times by water released from Stony Brook Reservoir. Prior to 1960, some regulation by mills upstream. Low flow completely regulated by Boston Edison Co. powerplant prior to 1954.
Neponset River At Norwood, Ma	Flow regulated by mills and reservoirs upstream. Flow affected by several diversions upstream for municipal and industrial use.
East Branch Neponset River At Canton, Ma	Flow regulated by Forge, Bolivar, Massapoag, and Reservoir Ponds, and other ponds upstream. Flow affected by diversions for municipal supply of Canton and Stoughton.
Wading River Near Norton, Ma	Flow regulated to some extent by Lake Mirimichi and other lakes and reservoirs upstream. Diversion

Table 4.5 Regulation of streams included in the streamflow database

Station Name	Regulation
	upstream for municipal supply of Attleboro and small diversions to and from basin for other municipal supplies.
Quinsigamond River At North Grafton, Ma	Some regulation by Lake Quinsigamond 2.3 miles upstream and by ponds upstream.
Little River Near Oxford, Ma	Flow regulated by Buffumville Lake since 1958 (Reservoirs in Thames River basin) and by other reservoirs upstream. July 1982 to about January 1983, flow affected by draining of Buffum Pond. Prior to 1958, flow regulated by mill upstream.
Millers River Near Winchendon, Ma	Flow regulated by powerplant and by Lake Monomonac and other reservoirs upstream.
Priest Brook Near Winchendon, Ma	Prior to 1962, occasional diurnal fluctuation at low flow by mill upstream; prior to 1953, regulation at low flow by mill and ponds.
Millers River At South Royalston, Ma	Flow regulated by Lake Manomonac and other reservoirs, by mills and powerplants prior to 1955, and at high flow by Birch Hill Reservoir since 1941 (Reservoirs in Connecticut River basin).
East Branch Tully River Near Athol, Ma	Flow regulated by Tully Lake since 1948 (Reservoirs in Connecticut River basin).
Millers River At Erving, Ma	Flow regulated by powerplants and by Lake Monomonac and other reservoirs; high flow regulated by Birch Hill Reservoir 22 miles upstream since 1941 and Tully Lake since 1948. Greater regulation by powerplants prior to 1966.
Deerfield River At Charlemont, Ma	Flow regulated by Somerset Reservoir, since 1924 by Harriman Reservoir, and by several powerplants upstream.
North River At Shattuckville, Ma	Diurnal fluctuation at times caused by mill upstream; because storage capacity is small, daily flows are not affected appreciably. Prior to 1950, greater regulation by mill.
Deerfield River Near West Deerfield, Ma	Flow regulated since 1913 by Somerset Reservoir, since 1924 by Harriman Reservoir, and by several powerplants upstream.
Connecticut River At Montague City, Ma	Flow regulated by powerplants and by First Connecticut and Second Connecticut Lakes, Lake Francis, Moore and Comerford Reservoirs, and other reservoirs, combined usable capacity, about 43,400,000,000 cubic feet.
Mill River At Northampton, Ma	Flow regulated by mill upstream.
Ware River Near Barre, Ma	Prior to August 1955, slight regulation at low flow at times by Long Pond. Flow regulated by Barre Falls Reservoir since 1958. Diversion at times since 1955 from 6.5 square miles upstream of station for municipal supply of Fitchburg.
Ware River At Intake Works Near Barre, Ma	Figures of discharge include diversion as needed for Boston metropolitan district during period October 15 to June 14 of each year and at other times for emergency flood-control purposes as authorized by U.S. Army Corps of Engineers; diversion began in March 1931. Flow regulated by Barre Falls Reservoir 4.3 miles upstream (see station 01172500) since 1958. Diversion at times since 1955 from 6.5 square miles upstream for municipal supply of Fitchburg.
Ware River At Gibbs Crossing, Ma	Diversion at times: Since March 1931 from 96.3 square miles for supply of Boston metropolitan district and since 1955 from 6.5 square miles for municipal supply of Fitchburg. Flow regulated by mills upstream and by Barre Falls Reservoir (see station 01172500) since 1958.

Table 4.5 Regulation of streams included in the streamflow database

Station Name	Regulation
East Branch Swift River Near Hardwick, Ma	No flow at times during several years.
Swift River At West Ware, Ma	Flow regulated since August 1939 by Quabbin Reservoir, usable capacity, 53.8 billion cubic feet. Diversion from Ware River to Quabbin Reservoir since 1940, from Quabbin Reservoir to Wachusett Reservoir since 1941, from Quabbin Reservoir to Chicopee Valley aqueduct since 1950, and from Quabbin Reservoir to city of Worcester at times since 1966.
Quaboag River At West Brimfield, Ma	Slight diurnal fluctuation at low flow caused by mill upstream prior to 1956; regulation much greater prior to 1938. High flow slightly affected by retarding reservoirs since 1965.
Chicopee River At Indian Orchard, Ma	Diversion since 1941 from 186 square miles in Swift River basin and at times since 1931 from 97 square miles in Ware River basin for Boston metropolitan district; since 1950, for Chicopee; since 1952, for South Hadley; at times since 1966 for Worcester; at times since 1955 from 6.5 square miles in Ware River basin for Fitchburg. Diversion from Ludlow Reservoir for Springfield and, prior to 1952, for Chicopee. Flow regulated by powerplants upstream, by Quabbin Reservoir 21 miles upstream on Swift River since 1939, by Barre Falls Reservoir on Ware River since 1958, by Conant Brook Reservoir since 1966, and by smaller reservoirs.
North Nashua River At Fitchburg, Ma	Flow regulated by mills and reservoirs upstream. Flow affected by diversions for municipal use.
Middle B Westfield River At Goss Heights, Ma	Some diurnal fluctuation at low flow prior to 1952 caused by mill upstream. Flow regulated by Littleville Lake (Reservoirs in Connecticut River basin) since 1965.
West Branch Westfield River At Huntington, Ma	Prior to 1950, some diurnal fluctuation at low flow caused by small mill upstream.
Westfield River Near Westfield, Ma	Flow regulated by Borden Brook Reservoir, Cobble Mountain Reservoir since 1931, Knightville Reservoir since 1941, and Littleville Lake since 1965. High flow slightly affected by retarding reservoirs since 1963. Diversion fromm Little River for municipal supply of Springfield.
West Branch Farmington River Near New Boston, Ma	Flow regulated by Otis Reservoir 7.0 miles upstream on Fall River. High flow slightly affected by retarding reservoirs since 1966.
East Branch Housatonic River At Coltsville, Ma	Flow regulated by powerplants upstream and, since 1949, by Cleveland Brook Reservoir, usable capacity, 214,000,000 cubic feet, 5.4 miles upstream; regulation greater prior to 1955. Diversion upstream from Cleveland Brook Reservoir for municipal supply of Pittsfield since May 1950.
Housatonic River Near Great Barrington, Ma	Regulation at low flow by powerplants upstream. High flow slightly affected by retarding reservoir since 1973.
Hoosic River At Adams, Ma	Diversion upstream for municipal supply of Adams. Some diurnal fluctuation by mill upstream prior to 1961. Flow regulated by Cheshire Reservoir 5.1 miles upstream.
North Branch Hoosic River At North Adams, Ma	Infrequent diurnal fluctuation at low flow by mill upstream; more frequent fluctuation prior to 1948.
Hoosic River Near Williamstown, Ma	Prior to 1966, slight diurnal fluctuation at low flow caused by mills upstream. Some regulation by Cheshire Reservoir 16 miles upstream.
Green River At Williamstown, Ma	Slight diurnal fluctuation at times caused by mill upstream.
Connecticut	

Table 4.5 Regulation of streams included in the streamflow database

Station Name	Regulation
Quinebaug R At Quinebaug,Ct.	Flow regulated by East Brimfield and Westville Lakes, and by smaller reservoirs upstream.
Mount Hope R Nr Warrenville, Ct.	Occasional regulation from ponds upstream.
Connecticut R At Thompsonville, Ct	Flow regulated by power plants, by diversion from Chicopee River basin and by First Connecticut and Second Connecticut Lakes, Lake Francis, Moore and Comerford Reservoirs, Quabbin Reservoir, and other reservoirs, combined usable capacity, about 107 billion cubic feet.
West Branch Farmington R At Riverton, Ct.	Flow regulated by Otis and West Branch Reservoirs and Colebrook River Lake.
Housatonic R At Falls Village,Ct.	Low flow completely regulated by power plant of Connecticut Light and Power Company. High flow is regulated by flood-control reservoirs from 20.5 square miles in the Blackberry River basin, but does not affect monthly runoff appreciably.
Rhode Island	
Woonasquatucket River At Centerdale, Ri	Some regulation by reservoirs upstream; regulation greater prior to 1956. Discharge figures prior to 1966 included leakage around station through bypass canal; leakage negligible subsequently.
Blackstone River At Woonsocket, Ri	Flow regulated by powerplants, by West Hill Reservoir since May 1961, and by other reservoirs upstream. Extremes and figures of daily discharge include flow diverted from Nashua River basin and, at times since January 1966, from Quabbin Reservoir for supply of Worcester, MA, and, prior to July 1964, flow diverted around station in Hamlet Trench.
Branch River At Forestdale, Ri	Occasional regulation by pond upstream. Prior to 1957, greater regulation by mills and reservoirs upstream.
South Branch Pawtuxet River At Washington, Ri	Flow regulated by Flat River Reservoir 2 miles upstream, usable capacity, 250,000,000 cubic feet, and smaller reservoirs. Prior to May 1972, diversion from Carr Pond for municipal supply of Coventry, Warwick, and West Warwick.
Hunt River Near East Greenwich, Ri	Flow affected by diversions for supply of East Greenwich, North Kingstown, Warwick, and Quonset Point (formerly U.S. Naval establishments).
New Hampshire	
Lamprey River Near Newmarket, Nh	Some regulation by Pawtuckaway and Mendums Ponds. These reservoirs have a usable capacity of about 600,000,000 cubic feet.
Ashuelot River At Hinsdale, Nh	Flow regulated by Surry Mountain Lake 33 miles upstream since 1942 and by Otter Brook Lake 29 miles upstream on Otter Brook since 1958 (Reservoirs in Connecticut River basin). Diurnal fluctuation by mills upstream.
New York	
Hoosic River Near Eagle Bridge Ny	Diurnal fluctuation at medium and low flow caused by powerplants upstream from station.

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Appendix A Sample meteorological data file

The following is a sample meteorological data file showing the beginning of the file and the first six years of meteorological data for Boston's Logan International Airport.

```
888
190770
BOSTON/LOGAN INT'L ARPT
 4.23666666666667E+0001
 7.10333333333333E+0001
 1 1920     29.5     12.5     24.8      2.72
 2 1920     34.6     20.6     32.5      4.11
 3 1920     48.0     30.5     11.0      3.72
 4 1920     52.1     38.0      2.0      5.68
 5 1920     61.8     47.5      0.0      5.26
 6 1920     74.1     57.6      0.0      5.78
 7 1920     81.4     63.4      0.0      1.56
 8 1920     78.9     65.2      0.0      2.32
 9 1920     72.9     57.6      0.0      1.90
10 1920     68.5     51.0      0.0      1.64
11 1920     48.4     35.0      1.8      5.46
12 1920     41.7     29.5      5.5      3.89
 1 1921     41.5     25.8      1.6      1.80
 2 1921     39.6     25.5     23.2      2.64
 3 1921     55.8     36.7      0.0      1.92
 4 1921     59.5     44.0      0.0      4.62
 5 1921     66.1     50.0      0.0      3.63
 6 1921     77.1     59.3      0.0      3.58
 7 1921     80.3     66.2      0.0     11.69
 8 1921     77.7     61.5      0.0      1.63
 9 1921     76.9     60.1      0.0      1.22
10 1921     63.8     46.6      0.0      1.24
11 1921     47.7     35.4      5.7      6.19
12 1921     38.5     24.1      4.4      2.38
 1 1922     34.1     20.3      2.7      1.41
 2 1922     39.8     24.3     15.5      2.64
 3 1922     47.8     31.8     10.1      4.30
 4 1922     57.7     39.7      3.3      2.48
 5 1922     70.9     52.0      0.0      5.34
 6 1922     76.5     60.8      0.0      8.05
 7 1922     79.7     64.4      0.0      2.63
```

8	1922	77.4	63.4	0.0	4.75
9	1922	73.2	57.1	0.0	3.65
10	1922	63.9	46.3	0.0	1.97
11	1922	50.1	37.4	0.9	0.84
12	1922	37.3	24.5	14.7	3.01
1	1923	34.4	19.5	25.3	6.07
2	1923	30.5	16.7	14.4	1.48
3	1923	42.5	25.2	10.6	2.49
4	1923	57.9	38.4	0.0	5.26
5	1923	66.5	48.6	0.0	0.83
6	1923	79.0	59.6	0.0	2.03
7	1923	77.7	62.2	0.0	3.36
8	1923	78.1	60.5	0.0	2.07
9	1923	71.6	57.1	0.0	0.38
10	1923	63.6	47.5	0.0	3.37
11	1923	51.5	37.8	0.0	2.59
12	1923	46.6	34.3	3.0	4.99
1	1924	40.5	23.3	8.5	3.27
2	1924	33.7	19.8	10.4	2.61
3	1924	44.3	31.6	7.4	2.04
4	1924	54.9	39.6	3.0	3.79
5	1924	63.6	48.8	0.0	2.81
6	1924	75.1	58.2	0.0	1.07
7	1924	82.9	64.8	0.0	2.04
8	1924	79.5	64.4	0.0	6.86
9	1924	70.0	54.4	0.0	6.96
10	1924	63.3	45.9	0.0	0.06
11	1924	52.7	37.1	0.5	1.93
12	1924	38.8	23.4	0.2	1.48
1	1925	34.9	19.4	20.7	3.97
2	1925	45.3	30.8	0.0	1.55
3	1925	51.5	34.6	0.0	5.21
4	1925	58.1	41.1	0.0	2.48
5	1925	66.5	48.4	0.0	2.57
6	1925	80.7	61.1	0.0	4.59
7	1925	80.5	64.1	0.0	3.54
8	1925	80.0	62.3	0.0	1.40
9	1925	72.1	56.0	0.0	3.45
10	1925	57.0	41.9	0.0	4.03
11	1925	51.3	36.0	0.0	4.16
12	1925	39.5	27.7	0.5	5.20

Appendix B Sample USGS streamflow file

This is a sample USGS streamflow data file showing the beginning of the file and the first several weeks of streamflow data for the Shawsheen River new Wilmington, Massachusetts.

```
# US GEOLOGICAL SURVEY
# DAILY MEAN DISCHARGE DATA
#
# Station name  : Shawsheen River Near Wilmington, Ma
# Station number: 01100600
# latitude (ddmmss)............................ 423405
# longitude (dddmmss).......................... 0711255
# state code................................... 25
# county....................................... Middlesex
# hydrologic unit code......................... 01070002
# basin name................................... Merrimack
# drainage area (square miles)................. 36.5
# contributing drainage area (square miles)..... 36.5
# gage datum (feet above NGVD)................. 80.44
# base discharge (cubic ft/sec)................ 300
# WATSTORE parameter code...................... 00060
# WATSTORE statistic code...................... 00003
# Discharge is listed in the table in cubic feet per second.
#
# Daily mean discharge data were retrieved from the
# National Water Information System files called ADAPS.
#
# Format of table is as follows.
# Lines starting with the # character are comment lines describing the data
# included in this file.  The next line is a row of tab-delimited column
# names that are Date and Discharge.  The next line is a row of tab-delimited
# data type codes that describe a 10-character-wide date (10d) and an
# 8-character-wide numeric value for discharge (8n).  All following lines are
# rows of tab-delimited data values of date (year.month.day) and discharge.
#
# NOTE this file was requested from the NWIS-W software package
# on Mon Sep 21 15:30:25 1998
#       Dates are now in  format.
#
# ----Date Range In File----
# 1 11/21/1963-09/30/1996
Date  Discharge   Flags
10s   8n    2s
11/21/1963  35    0
11/22/1963  34    0
11/23/1963  33    0
11/24/1963  42    0
11/25/1963  54    0
```

11/26/1963	59	0
11/27/1963	54	0
11/28/1963	46	0
11/29/1963	43	0
11/30/1963	96	0
12/01/1963	231	0
12/02/1963	202	0
12/03/1963	145	0
12/04/1963	108	0
12/05/1963	87	0
12/06/1963	74	0
12/07/1963	65	0
12/08/1963	58	0
12/09/1963	62	0
12/10/1963	94	0
12/11/1963	120	0
12/12/1963	103	0
12/13/1963	83	0
12/14/1963	72	0
12/15/1963	60	0
12/16/1963	49	0
12/17/1963	43	0
12/18/1963	37	0
12/19/1963	35	0
12/20/1963	33	0
12/21/1963	31	0
12/22/1963	29	0
12/23/1963	28	0
12/24/1963	27	0
12/25/1963	28	0
12/26/1963	30	0
12/27/1963	31	0
12/28/1963	29	0
12/29/1963	27	0
12/30/1963	25	0
12/31/1963	24	0
01/01/1964	22	0
01/02/1964	26	0
01/03/1964	28	0
01/04/1964	31	0
01/05/1964	33	0
01/06/1964	34	0
01/07/1964	36	0
01/08/1964	38	0
01/09/1964	38	0
01/10/1964	41	0
01/11/1964	45	0
01/12/1964	43	0
01/13/1964	40	0
01/14/1964	33	0
01/15/1964	30	0
01/16/1964	30	0
01/17/1964	29	0
01/18/1964	29	0
01/19/1964	27	0

Appendix C Sample reservoir summary file

This is a sample of a summary file produced by the FYE when the *Summary file* option is selected from the *File* menu.

```
Firm Yield Estimator Summary File
Title:
Atkins Reservoir - Amherst, Massachusetts
Comments:
This analysis assumes a constant surface area for the reservoir
of 0.063 square miles.

Meteorological Data
AMHERST
Latitude:  42.3833
Longitude:  72.5333
Period of record:  1926 to 1993

Streamflow Data
Mill River At Northampton, Ma
Latitude:  42.3181
Longitude:  72.6558
Period of record:  1938 to 1996

Missing meteorological data were replaced with average monthly
values.
The meteorological station is approximately   7.7 miles from the
streamgauge.

Reservoir Data
Area of the reservoir watershed:  5.85 square miles
Area of the streamgauge watershed:  54.0 square miles
Reservoir capacity:  1000 million gallons
Required releases:  18.6 million gallons per month

Bathymetry Data
Order of the polynomial used to characterize bathymetry:  0
Constant coefficient  :  0.063

Peak Use Factors
January  :  1.08
```

```
February :  1.03
March    :  1.20
April    :  1.15
May      :  1.19
June     :  1.10
July     :  1.19
August   :  1.13
September:  0.85
October  :  0.56
November :  0.54
December :  0.99

Evaporation Rate Data (in inches per month)
Evaporation rates were estimated from meteorological data.
Reservoir longitude:  72.484
Reservoir elevation:  470 feet
January  :  1.00
February :  1.38
March    :  2.52
April    :  3.88
May      :  5.65
June     :  6.60
July     :  6.98
August   :  6.01
September:  4.19
October  :  2.65
November :  1.43
December :  0.97

Withdrawals by Other Users
January  :  0
February :  0
March    :  0
April    :  0
May      :  0
June     :  0
July     :  0
August   :  0
September:  0
October  :  0
November :  0
December :  0

Input Data for the Streamgauge Transform
Average watershed elevation:  850 feet
Mean channel slope:  182 feet per mile
```

Maximum soil retention: 6.39 inches
Average annual precipitation: Calculated from meteorological data
Average annual snowfall: Calculated from meteorological data
Generating 1,000 Year Sequence of Meteorological Data
The entire period of record was used to generate the 1,000 year sequence of meteorological data.

Actual meteorological data were used in the firm yield analysis.
Data between the years 1939 and 1993 were used in the analysis.

The scanning yield of the reservoir is 3.188 million gallons per day.
The reservoir did not refill during 3.7% of the years in the scanning analysis.
The firm yield of the reservoir is 3.322 million gallons per day.
The reservoir did not refill during 3.7% of the years in the firm yield analysis.