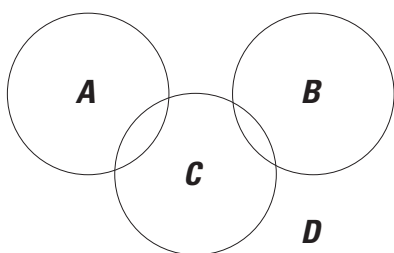


Prepared in cooperation with the Massachusetts Department of Environmental Protection

Determination of Dilution Factors for Discharge of Aluminum-Containing Wastes by Public Water-Supply Treatment Facilities into Lakes and Reservoirs in Massachusetts



Scientific Investigations Report 2011–5136



Cover. *A, B*, Flowing and drying sludge lagoons receiving filter backwash effluent, Northampton Mountain Street Water Treatment Plant, Northampton, Massachusetts (photos by Andrew J. Massey); *C*, Sampling site at mouth of diversion pipe from Perley Brook at discharge to Crystal Lake in Gardner, Massachusetts (photo by Melissa J. Weil); *D*, Sampling site at unnamed tributary to Haggetts Pond in Andover, Massachusetts at the northwest shore of the pond (photo by Andrew J. Massey).

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
inch (in)	2.54	centimeter (cm)
Area		
acre	4,047	square meter (m ²)
Volume		
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m ³)
Flow rate		
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m ³ /s)
Mass		
pound, avoirdupois (lb)	0.4536	kilogram (kg)

Determination of Dilution Factors for Discharge of Aluminum-Containing Wastes by Public Water-Supply Treatment Facilities into Lakes and Reservoirs in Massachusetts

By John A. Colman, Andrew J. Massey, and Sara B. Levin

Abstract

Dilution of aluminum discharged to reservoirs in filter-backwash effluents at water-treatment facilities in Massachusetts was investigated by a field study and computer simulation. Determination of dilution is needed so that permits for discharge ensure compliance with water-quality standards for aquatic life. The U.S. Environmental Protection Agency chronic standard for aluminum, 87 micrograms per liter ($\mu\text{g/L}$), rather than the acute standard, 750 $\mu\text{g/L}$, was used in this investigation because the time scales of chronic exposure (days) more nearly match rates of change in reservoir concentrations than do the time scales of acute exposure (hours).

Whereas dilution factors are routinely computed for effluents discharged to streams solely on the basis of flow of the effluent and flow of the receiving stream, dilution determination for effluents discharged to reservoirs is more complex because (1), compared to streams, additional water is available for dilution in reservoirs during low flows as a result of reservoir flushing and storage during higher flows, and (2) aluminum removal in reservoirs occurs by aluminum sedimentation during the residence time of water in the reservoir. Possible resuspension of settled aluminum was not considered in this investigation. An additional concern for setting discharge standards is the substantial concentration of aluminum that can be naturally present in ambient surface waters, usually in association with dissolved organic carbon (DOC), which can bind aluminum and keep it in solution.

A method for dilution determination was developed using a mass-balance equation for aluminum and considering sources of aluminum from groundwater, surface water, and filter-backwash effluents and losses caused by sedimentation, water withdrawal, and spill discharge from the reservoir. The method was applied to 13 reservoirs. Data on aluminum and DOC concentrations in reservoirs and influent water were collected during the fall of 2009. Complete reservoir volume was determined to be available for mixing on the basis of verti-

cal and horizontal aluminum-concentration profiling. Losses caused by settling of aluminum were assumed to be proportional to aluminum concentration and reservoir area. The constant of proportionality, as a function of DOC concentration, was established by simulations in each of five reservoirs that differed in DOC concentration.

In addition to computing dilution factors, the project determined dilution factors that would be protective with the same statistical basis (frequency of exceedence of the chronic standard) as dilutions computed for streams at the 7-day-average 10-year-recurrence annual low flow (the 7Q10). Low-flow dilutions are used for permitting so that receiving waters are protected even at the worst-case flow levels. The low-flow dilution factors that give the same statistical protection are the lowest annual 7-day-average dilution factors with a recurrence of 10 years, termed 7DF10s. Determination of 7DF10 values for reservoirs required that long periods of record be simulated so that dilution statistics could be determined. Dilution statistics were simulated for 13 reservoirs from 1960 to 2004 using U.S. Geological Survey Firm-Yield Estimator software to model reservoir inputs and outputs and present-day values of filter-effluent discharge and aluminum concentration.

Computed settling velocities ranged from 0 centimeters per day (cm/d) at DOC concentrations of 15.5 milligrams per liter (mg/L) to 21.5 cm/d at DOC concentrations of 2.7 mg/L. The 7DF10 values were a function of aluminum effluent discharged. At current (2009) effluent discharge rates, the 7DF10 values varied from 1.8 to 115 among the 13 reservoirs. In most cases, the present-day (2009) discharge resulted in receiving water concentrations that did not exceed the standard at the 7DF10. Exceptions were one reservoir with a very small area and three reservoirs with high concentrations of DOC. Maximum permissible discharges were determined for water-treatment plants by adjusting discharges upward in simulations until the 7DF10 resulted in reservoir concentrations that just met the standard. In terms of aluminum flux, these discharges ranged from 0 to 28 kilograms of aluminum per day.

Introduction

Treatment of water supplies by aluminum sulfate (alum) coagulation, settling, and filtration prior to distribution has been a common practice in the United States (Gruninger and Westerhoff, 1974) and is currently used in many water-treatment plants in Massachusetts (Mass.). The effect of this treatment is settling and removal of aluminum hydroxide floc with associated coprecipitated contaminants.

Typically, alum is applied in dry form or as a concentrated liquid to the supply water. The aluminum combines with hydroxide from the water and forms an aluminum hydroxide precipitate. Contaminants such as dissolved natural organic matter, colloidal inorganic or organic particles, and dissolved ions such as phosphate and heavy metals can be removed. The precipitate is removed from the supply in gravity settling basins and by filtration, often through sand filters. Waste solids from the alum-coagulation process can derive from both the coagulation-sedimentation-basin wastewater and from filter backwash. In this report the wastes are referred to as filter-backwash effluent. The filter-backwash effluent is typically discharged from the treatment plant to a settling basin, with overflow to a surface-water body—a stream, lake, or reservoir. This report is concerned with establishing permit requirements for discharge of aluminum-containing filter-backwash effluent from public water supply (PWS) treatment facilities to lakes or reservoirs. In Massachusetts, permits for discharge are regulated by the Massachusetts Department of Environmental Protection (MassDEP) under the National Pollution Discharge Elimination System (NPDES).

Many of the discharged filter-backwash effluents from PWS treatment facilities contain aluminum concentrations that are above ambient water-quality standards but that may be acceptable for discharge if sufficiently diluted by the receiving waters. Typically, discharge permits account for dilution by use of dilution factors. A dilution factor (DF) is the ratio of concentration in the effluent to concentration in the receiving water after mixing in the receiving water.

DF s are routinely computed for effluents discharged to streams (without significant instream ambient contaminant concentrations) as the ratio of flow in the stream to flow in the effluent (U.S. Environmental Protection Agency, 2008):

$$DF = (Q_p + Q_e)/Q_e \quad (1)$$

where

Q_p is the flow in the stream, and
 Q_e is the flow of the effluent.

In order to ensure that DF s are protective of aquatic life at the range of flows that might occur, permits for discharge of metals to streams are based on low-flow conditions, when little stream water is available for dilution. Permitting for metals discharge in Massachusetts defines low-flow conditions as the

7-day-average 10-year-recurrence annual low flow (7Q10) and sets discharge limits based on the DF at that flow value.

Filter-backwash discharges from PWS can be as high as one million gallons per day or 1.55 cubic feet per second (ft^3/s), and diluting stream flow discharges can be as small as a few cubic feet per second at low flow. Thus, if DF s for reservoirs were estimated as they are for streams, low DF values (less than 10) could result during low flow, and many current discharges would exceed the standard. However, additional processes that would likely increase the minimum DF values are involved for dilution of effluents entering reservoirs, as compared to effluents entering streams. These are (1) that additional water is available for dilution in reservoirs during low flow because of reservoir flushing and storage during higher flows and (2) that aluminum removal occurs in reservoirs because of aluminum sedimentation during the residence time of water in the reservoir.

Another factor to consider when estimating the DF is the ambient concentration of aluminum from natural sources in the diluting stream or reservoir water. Aluminum concentration data from the U.S. Geological Survey (USGS) water-quality database (QWDATA) indicates that dissolved (0.45- μm filtrate) aluminum concentrations in Massachusetts surface-water samples collected during 1991–2009 ranged from undetected to 383 micrograms per liter ($\mu\text{g/L}$), with a median concentration value of 14.5 $\mu\text{g/L}$ (n equals 261) and that total concentrations ranged from undetected to 519 $\mu\text{g/L}$, with a median concentration value of 100 $\mu\text{g/L}$ (n equals 65). The chronic and acute toxicity water-quality standards for aluminum are 87 and 750 $\mu\text{g/L}$, respectively, as total aluminum (U.S. Environmental Protection Agency, 2010). Therefore, there may be some filter-backwash effluent disposal sites with aluminum concentrations in the receiving waters that would already exceed the U.S. Environmental Protection Agency chronic standard.

Whereas accounting for all the processes affecting aluminum concentration could result in accurate DF s for aluminum discharge into reservoirs, the use of DF s in permitting may be more complex than the use of DF s for streams, which is based only on the ratio of receiving water flow to effluent flow. The flow-ratio DF for streams, defined at low flow (7Q10), is a unique value and can be applied to any effluent concentration to determine concentration in the receiving water after dilution. In particular, the effluent concentration can be computed that would result, after dilution, in a receiving water concentration that just meets the standard, and this can be used as an upper-limit effluent concentration for permitting discharge.

When the DF also depends on processes like aluminum sedimentation in the reservoir, the DF is not independent of the concentration in the effluent discharge. Typically, the DF for reservoirs increases as the concentration discharged increases. Under these circumstances, statistical analysis of the concentrations in the receiving water resulting from a given

discharge and associated daily *DFs* must be used to choose a discharge concentration-dilution combination that will protect the reservoir. The discharge concentration-dilution combination that is selected should afford the receiving water the same protection on the basis of frequency of standard exceedence as that resulting for discharge to streams when the flow-ratio dilution factor, based on the 7Q10 discharge, is used.

Purpose and Scope

A method is described here that uses numerical solutions to a mass-balance equation to determine *DF* values for discharge of filter-backwash effluent that contains aluminum to reservoirs and lakes in Massachusetts. The method includes the effects of reservoir storage, aluminum sedimentation, and ambient concentration of aluminum in the receiving water. Possible resuspension of aluminum from the sediment is not considered. A method is described to use the resulting *DFs* to determine concentrations in filter-backwash effluent that would result in the same statistically equivalent protection against exceeding a standard for reservoirs that is currently provided for streams. Sufficient details are given so that the methods can be applied by report users with access to numerical-solution and statistical-analysis computer software. The method was applied to 13 reservoirs in Massachusetts where aluminum-containing filter backwash is discharged. Chemical and discharge data required to apply the method to a reservoir are described. The report includes data collected for those reservoirs for which *DF* values were computed.

Previous Investigations

Although there have been no formal investigations of *DFs* for aluminum in reservoirs before this study, aspects of the question, including techniques for metals sampling and solute modeling in reservoirs, have been investigated. Sampling methods for trace metals, such as aluminum, are well documented (Wilde, 2004, 2006). Although no reservoir simulations of aluminum concentration are known to the authors, reservoir simulations of phosphorus concentration, another nonconservative element, have been conducted (Vollenweider, 1979). In the current study, the same approach is used for aluminum as Vollenweider (1979) has used for phosphorus, simulating the reservoir as a mixed reactor with solute removal by sedimentation as well as by outflow from the reservoir.

The aquatic chemistry of aluminum is well known. Chemical processes may enhance the removal of aluminum by precipitation (see, for example, Parkhurst and Appelo, 1999) or retain aluminum in solution, for example, by binding with dissolved organic carbon (DOC) (see, for example, Breault and others, 1996). Aluminum may also be deposited as sediment after incorporation on, and settling by, phytoplankton.

The Dilution-Factor Method

There are two parts to developing a method for computation of *DF* values for aluminum discharge to reservoirs. The first is developing the method for computing dilution at any given time for a given reservoir and discharge. This requires knowledge of mass-balance inputs and outputs of aluminum to and from the reservoir and numerical solution of an ordinary differential equation for concentration in the reservoir. The second part is developing a method for applying the reservoir *DFs* to permit writing that results in protection of the receiving water that is statistically comparable to the protection afforded by *DFs* determined at low flow (7Q10) for discharge to streams.

Calculating Dilution

As discussed in the Introduction section, more factors are involved in dilution of aluminum-containing effluents that discharge to reservoirs than in discharge to streams. The additional factors are (1) dilution by water stored in the reservoir after flushing at high flow, (2) in-reservoir losses of aluminum through sedimentation, and (3) occasional natural occurrence of aluminum at high concentration in input streams. High natural aluminum concentrations, usually associated with high concentrations of aluminum-stabilizing DOC, render receiving waters less effective at diluting aluminum discharged from treatment plants.

The method for computing *DF* values that includes these three factors requires the numerical integration of the reservoir mass-balance equation for aluminum-concentration change. The mass-balance equation is:

$$\frac{dC}{dt} = (Q_e C_e + Q_s C_s + Q_g C_g + Q_w C - A S_v C) / V \quad (2)$$

where

C	is the total aluminum concentration in the reservoir water,
Q_e	is the discharge of the filter-backwash effluent,
C_e	is the total aluminum concentration in the filter-backwash effluent,
Q_s	is the discharge of the streams that are influent to the reservoir,
C_s	is the total aluminum concentration in the stream,
Q_g	is the discharge of groundwater that is influent to the reservoir,
C_g	is the total aluminum concentration in the groundwater,
Q_w	is the sum of water withdrawal for water supply and the downstream discharge from the reservoir,

- A is the area of the reservoir,
 S_v is the apparent settling velocity of total aluminum in the reservoir,
 V is the volume of the reservoir subject to mixing, and
 t is time.

The numerical integration of the mass-balance equation results in C , the aluminum concentration in the reservoir at any time t , and requires the specification of the variables shown in on the right side of equation 2. The DF value at any time t is then

$$DF = C_e / C. \quad (3)$$

Equation 2 was solved numerically in this study using the MatLab differential equation solver named "ode45" (Shampine and Gordon, 1975; Dormand and Prince, 1980), as described in appendix 1.

Calculating the Settling Velocity

The settling velocity, used to compute the loss of aluminum due to settling to the bottom sediment, can be determined from successive solutions of equation 2, using trial settling velocities, initial conditions determined from field data, which would likely increase the minimum DF values, and the additional data requirements used to solve equation 2 previously described. Simulated aluminum concentrations are compared to measured concentrations after each simulation run, and the settling velocity is adjusted (increased if simulated concentration was greater than measured, or vice versa) until the best agreement of predicted and measured plots is obtained, as determined by visual inspection. Because sampling four times at monthly intervals generated too few data points, more formal statistical curve fitting was not possible.

Dilution at Low Flow

The second part of developing discharge permits appropriate for reservoirs requires statistical analysis of the DF daily values to determine the relation between the concentration in the effluent and the frequency of the aluminum discharge exceeding the standard after dilution in the receiving water. For this study, the aluminum standard is taken as the chronic standard of 87 $\mu\text{g/L}$. The chronic, rather than the acute, standard (750 $\mu\text{g/L}$) was selected in consultation with the Mass-DEP, because concentrations in reservoirs change relatively slowly—on the order of days. All exposures to aluminum in reservoirs, therefore, are likely to be chronic exposures. For permitted limits, the frequency of standard exceedence for the reservoir should be at the same rate as for discharge to a stream regulated by a flow-ratio DF at low flow (7Q10).

Permits based on DF at the 7Q10 flow for discharge to streams set limits that would result in the highest annual 7-day-average concentration in the stream exceeding the standard, on average, once every 10 years. By analogy for discharge to reservoirs, permitting should result in the highest annual 7-day-average concentration in the reservoir exceeding the standard, on average, once in every 10 years. Because DF s for discharge to reservoirs are proportional to the reciprocal of reservoir concentration (equation 3), the highest annual 7-day-average reservoir concentration with a recurrence of 10 years would correspond to the lowest annual 7-day-average DF with a recurrence of 10 years. By analogy with flow, this is termed the 7DF10.

Unlike 7DF10 values for discharge to streams, the 7DF10 value for discharge to reservoirs is a function of effluent discharge concentration (C_e). That is because the settling and the reservoir-discharge terms for aluminum in equation 2 depend on the aluminum concentration in the reservoir, which in turn is affected by the concentration in the effluent discharge. For every C_e value, there is a corresponding 7DF10. But there is only one 7DF10 and C_e pair that results in a reservoir concentration that just meets the chronic water-quality standard. Determination of this pair may necessitate computation of several 7DF10– C_e pairs that result in reservoir concentrations that bracket the standard, followed by interpolation to the values that result in the chronic standard being met in the reservoir.

In practice, the long DF records required to determine the 7DF10 are obtained by solving equation 2 for C each day. The daily concentrations are used to compute daily DF s from equation 3 and analyzed for a 7-day running average. The lowest 7-day average is selected for each year. The yearly data are fitted to a known distribution; a log Pearson type III distribution gave the best fit in this investigation. Finally, the DF at the 10th percentile is selected from the fitted distribution. The software SWSTAT is available to compute the 7-day averages, to select annual values, and to fit the frequency distribution (U.S. Geological Survey, 2002).

Data Requirements

Long records of hydrologic data are required to determine accurate 7DF10 values. This project determined 7DF10 values from daily DF values computed from 1960 to 2004. The reservoir input- and output-flow data used in the DF calculations represented hydrologic conditions over this period, but the effluent discharge and effluent concentration data were based on present-day practices for the water-treatment facilities. Therefore, the study results are for present practices for aluminum discharge and hydrologic variation that is representative of the 1960–2004 period. The implied assumption in application of the results is that future hydrologic variation will be similar to past variation.

Flows and Reservoir Volumes

Past investigations of reservoir flow and capacities in Massachusetts have produced hydrologic- analysis software for computing flows and volumes. For streamflow, the Massachusetts Sustainable Yield Estimator can be used (Archfield and others, 2010). Groundwater input and volume changes in reservoirs can be determined from the Firm-Yield Estimator¹ (Waldron and Archfield, 2006; Archfield and Carlson, 2006; Levin and others, 2011). Reservoir bathymetry, which is necessary for the volume change estimates, is available from the water suppliers or may be obtained by bathymetric-survey techniques.

Filter-Backwash Effluent Flows

Values of filter-backwash effluent flows are available from records kept by the PWS operators. Monthly average values and maxima are reported on Discharge Monitoring Requirement forms (K. Keohane, Massachusetts Department of Environmental Protection, written commun., 2010). More detailed records are also usually kept by suppliers and may be available on request.

Water Quality

Aluminum-concentration estimates are needed for influent streams and groundwater and for filter-backwash effluent discharge. In addition, aluminum concentrations in the reservoirs are needed for initial concentrations in the settling-velocity trial simulations and to determine if simulated results match measured results. DOC concentrations in the reservoirs are also needed for simulations, because settling velocity depends on DOC.

Application of the Dilution-Factor Method to Reservoirs

Application of the dilution-factor method to discharges of reservoirs requires that daily reservoir input flows and aluminum concentrations be computed so that daily in-reservoir aluminum concentrations can be computed by solution of equation 2 and daily dilution factors computed from equation 3. Then the 7-day annual mean lowest dilution factor with a 10-year recurrence (7DF10) is computed and used with the discharge aluminum concentration in equation 3 to determine the reservoir concentration that would apply at that low level of dilution.

¹ Firm yield is the maximum volume of water that can be withdrawn from a reservoir without causing the reservoir to fail during drought conditions.

If the computed reservoir aluminum concentration that results happens to be at the chronic standard, then the discharge concentration used would be the amount permitted for discharge. If the reservoir aluminum concentration is below the chronic standard, then a higher discharge concentration (double, for example) is chosen and then analysis begins again at number 2.

Determination of a 7DF10 and C_e pair that results in a reservoir concentration that just meets the chronic water-quality standard may necessitate computation of several 7DF10– C_e pairs that result in reservoir concentrations that bracket the chronic standard. Interpolation can then determine the values that result in the chronic standard being met in the reservoir.

Reservoirs Studied

The dilution-factor method was applied to 13 reservoirs in this investigation to assess the discharge concentration that would meet the chronic aluminum standard (table 1). Of these, five were chosen for more intensive sampling used for determining settling velocities of aluminum in the reservoirs.

During discussion between the USGS and MassDEP before the project was initiated, 21 candidate reservoirs were identified for the study of aluminum dilution. For reasons of unavailability of data, special discharge circumstances, or determination that no aluminum was being discharged to a reservoir, 8 of the original 21 were not further investigated for dilution factors (appendix 2).

Flow, Area, and Volume Calculations

Daily streamflow inputs to reservoirs (Q_s) were simulated using the Massachusetts Sustainable-Yield Estimator (Archfield and others, 2010) for the period October 1960 through September 2004. At the five reservoir sites chosen for settling-velocity determinations, the flow estimates were extended through December 2009, so that simulation data could be appropriately compared to measured data collected in fall 2009. Daily groundwater input and output flows (Q_g), daily reservoir volumes (V), and reservoir outflows, a component of Q_w , were estimated with the Firm-Yield Estimator (Waldron and Archfield, 2006; Archfield and Carlson, 2006; Levin and others, 2011), which was modified to run on a daily time step. Daily water use, a component of Q_w , was estimated by disaggregating average reported monthly withdrawal volumes from 2005 to 2009. Discharge flows of the filter-backwash effluent (Q_e) were determined variously from reporting from the suppliers to MassDEP or from more detailed descriptions made by the suppliers to USGS (appendix 3).

Regulation of reservoirs constituted additional inputs and withdrawals not dependent on the hydrologic cycle, and data on these were provided with a variable amount of detail from suppliers (appendix 3). Bathymetric surveys, needed for determining reservoir volume and surface area at different depths, were completed by boat survey or obtained from previous studies of the reservoirs (appendix 3).

Table 1. Massachusetts town surface-water supplies and reservoirs investigated for aluminum-discharge permitting.

[USGS, U.S. Geological Survey; *, reservoir was used to determine settling velocities of aluminum; WTP, water-treatment plant; WTF, water-treatment facility; permit number, the National Pollutant Discharge Elimination System (NPDES) permit number]

Facility	Permit number	Receiving water	Latitude (decimal degree)	Longitude (decimal degree)	USGS station number for reservoir
*Andover WTP	MAG640058	Haggetts Pond	42.646	-71.199	423844071115501
*Ashburnham/Winchendon WTP	MAG640045	Upper Naukeag Lake	42.655	-71.923	423919071552401
*Cambridge WTP	MAG640040	Fresh Pond Reservoir	42.385	-71.149	422305071090001
Clinton WTP	MAG640047	Unnamed small pond	42.412	-71.701	422443071420301
*Cohasset WTP	MAG640070	Lily Pond	42.224	-70.816	421326070485801
*Gardner WTF	MAG640041	Crystal Lake	42.584	-71.993	423501071593501
Manchester-by-the-Sea and Hamilton WTP	MAG640003	Gravelly Pond	42.599	-70.81	423555070483701
New Bedford WTP	MAG640069	Little Quittacas Pond	41.793	-70.921	414734070551401
Northampton WTP	MAG640034	Mountain Street Reservoir	42.401	-72.671	422404072401501
Salem and Beverly Water Supply Board	MAG640059	Wenham Lake Reservoir	42.59	-70.891	423523070532801
Weymouth WTP	MAG640031	Great Pond	42.156	-70.971	420920070581501
Winchester WTP	MAG640037	South Reservoir	42.444	71.116	422639071065601
Worcester WTP	MAG640052	Holden Reservoir #2	42.297	-71.867	421748071520001

Water-Sample Collection, Processing, and Chemical Analysis

Required water-quality samples include those used for aluminum input and output calculation, as well as those used for ancillary water-quality assessment. Thus, in addition to aluminum-concentration samples, samples were collected for determination of DOC concentrations used to assess effects on aluminum-settling velocity; and for measurements of pH, temperature, dissolved oxygen concentrations and conductance, all of which were used to assess aluminum solubility and mixing in the reservoirs.

Samples for aluminum analysis were collected using clean-sampling techniques (Wilde, 2004, 2006) and preserved on return to the Northborough, Mass., laboratory with 0.5 milliliter (mL) of concentrated HNO_3 per 125-mL polyethylene bottle. The acid-preserved samples were sent to the USGS National Water Quality Laboratory in Denver, Colorado (Colo.), for aluminum analysis after inbottle acid digestion (Hoffman and others, 1996). The analytical method was inductively coupled plasma-mass spectrometry (Garbarino and Struzeski, 1998). The reporting level was 5 $\mu\text{g/L}$.

Many aluminum devices, including boats, which may be in proximity to samples, make special care necessary during collection and processing of these samples to prevent sample contamination. Sampling equipment and bottles were contained in plastic bags and not exposed to boat surfaces.

Samples for DOC were filtered in the field with Aquaprep, 0.45- μm inline filters, and stored in prebaked, brown-glass, 125-mL bottles. Samples were acidified on return to the laboratory in Northborough, Mass., with 1.0 mL of 4.5 N H_2SO_4 . The acid-preserved samples were sent to the USGS National Water Quality Laboratory in Denver, Colo., for DOC analysis by ultraviolet-promoted persulfate oxidation and infrared spectrometry (Garbarino and Struzeski, 1998). The reporting level was 0.15 mg/L.

The field parameters pH, temperature, dissolved oxygen, and conductance were determined using a Eureka Manta multiprobe. Values can be read with the instrument lowered to the required depth in the reservoir or from samples poured into the multiprobe cup at the surface.

Depth-profile samples, collected for aluminum in two reservoirs, were obtained by pumping at the surface with a peristaltic pump on plastic tubing lowered to sampling depths. A Eureka multiprobe, lowered to sampling depths, measured pH, temperatures, conductances, and concentrations of dissolved oxygen of samples. The probe was calibrated for pH, conductance, and dissolved oxygen on a daily basis.

Samples for aluminum analysis for most reservoirs were collected during one reservoir visit in the fall of 2009. Samples were collected to determine aluminum concentrations in backwash discharge (C_e), input streams (C_s), and three-sample reservoir-surface composites (C). Samples from reservoirs selected for settling-velocity calculations were collected dur-

ing the late summer and fall 2009 (generally in four samplings spanning 3 months).

Groundwater aluminum concentrations (C_g) were determined from data retrieved from the USGS water-quality database QWDATA. The retrieval was from all groundwater sites in Massachusetts after 1991, when clean-sampling techniques were implemented for metals. Dissolved (filtered-sample) concentrations were used, the assumption being that most aluminum transport in the aquifer is in the dissolved state. The median concentration value of 10 $\mu\text{g/L}$ (n equals 452) was used. This value, 10 $\mu\text{g/L}$, was the method detection limit for many of the analyses. Use of the data median for the concentration of aluminum in groundwater, rather than a measured value for each reservoir, likely added little uncertainty to our model because groundwater fluxes (from the Firm-Yield Estimator described in the previous section) were small or zero for the reservoirs.

Quality Assurance of the Water-Quality Data

During the investigation, 27 quality-assurance (QA) samples were collected to assess error in aluminum and DOC measurements, including sample-bottle and acid blanks, standard reference samples, duplicate samples, and sample splits (table 2). QA results of the blank samples showed that possible contamination during sampling or sample handling or from sampling materials (the bottles and preservation acid) was insubstantial or did not occur. All concentrations measured for the four sampling-bottle blanks collected during the study were below detection for the respective analytes (table 2). Two samples of USGS standard reference solution (USGS T-195) submitted to the National Water Quality Laboratory as blind samples were within 4 percent of the known values (table 2). Concentrations of both aluminum and DOC in duplicate samples varied by about 1 percent. The good agreement for duplicates and standards and lack of contamination in blanks

indicated that the clean-sampling techniques applied during sampling collection and processing were adequate.

Water-Quality Results and Associations

Aluminum measured in the reservoirs ranged from a low of less than 6 $\mu\text{g/L}$ (below detection limit) to a high of 414 $\mu\text{g/L}$ (appendix 4). Concentrations of DOC in the reservoirs ranged from 1.5 to 15.5 mg/L , with a median value of 3.4 mg/L . The higher concentrations of DOC were likely dominated by humic compounds, which leach into water from wetland soils (fig. 1) (Aitkenhead-Peterson and others, 2003).

Aluminum can bind chemically with DOC so that high-DOC systems typically have high natural aluminum concentrations (as determined in Massachusetts by Breault and others, 1996). The binding of aluminum by DOC keeps aluminum in solution in the water column, whereas unbound aluminum would precipitate from solution once the solubility product for the precipitate, aluminum hydroxide, was exceeded. Iron and aluminum form complexes with DOC or colloidal oxyhydroxides mixed with DOC, which keep the metals from settling from the water column (Berner and Berner, 1996). Sampling of reservoirs and streams for this study shows an association between DOC and aluminum (fig. 2).

In the absence of DOC, the solubility of aluminum in water is low. Depending on what solid phase forms, solubility of aluminum could range to lower than 1 $\mu\text{g/L}$ for the pH range 4.7 to 7.0. The lower concentrations in equilibrium with gibbsite are energetically favored, but equilibrium with this phase is established more slowly than with the more soluble amorphous form of $\text{Al}(\text{OH})_3$ (fig. 3). The low solubility of aluminum indicates that much of the aluminum discharged to reservoirs would likely settle to the bed sediments and remain there. Removal of aluminum by settling of the precipitate likely contributes substantially to the settling-velocity term of equation 2.

Table 2. Results of quality-assurance evaluation of sampling for aluminum and dissolved organic carbon.

[Al, aluminum; DOC, dissolved organic carbon; $\mu\text{g/L}$, micrograms per liter; mg/L , milligrams per liter; USGS, U.S. Geological Survey; %, percent]

Quality assurance measure	Details	Number of samples	Result
Bottle blanks	Sample bottles were filled in the field with blank water, and were preserved with acid.	5 Al and 2 DOC	All concentrations less than the method detection limit—6 $\mu\text{g/L}$ for Al and 0.4 mg/L for DOC.
Standard reference sample	USGS standard reference water sample, number T-195.	2 Al	Mean relative error was 4%.
Duplicates at one time	Samples taken sequentially on one sampling occasion.	13 Al and 13 DOC	Mean relative error was 2.1% for Al and 1.2% for DOC.



Figure 1. Lily Pond, Cohasset, Massachusetts, showing riparian wetland button bush and brown water (here visible in the boat's wake) characteristic of dissolved organic carbon compounds.

High DOC is also associated with lower pH, because many of the DOC compounds are acids—particularly humic acids and fulvic acids (McKnight and others, 2003). A correlation between DOC and aluminum could conceivably be an effect of pH, rather than of DOC. The aluminum concentration data for reservoirs and streams plotted against pH (fig. 4) shows little correlation, however, indicating that pH is probably not the primary factor that controls aluminum concentration.

Aluminum Mixing in Reservoirs

Dilution factors depend on the mixing volume in the receiving water that is available for dilution. In streams, the whole streamflow is used as the dilution volume, even though complete dilution across the stream channel likely happens some distance downstream from the point of effluent discharge, usually from a pipe or channel. For reservoirs, the entire reservoir volume should be available

for dilution if mixing is rapid with respect to the rate of effluent discharge.

Mixing for reservoirs was investigated with vertical- and horizontal- profile sampling. Vertical profiles of two reservoirs show that, although temperature stratification occurs, typically with a thermocline at 6-m depth, aluminum concentrations are relatively constant above the thermocline and decrease somewhat below the thermocline (fig. 5). The absence of substantial vertical stratification of aluminum concentrations above the thermocline and the fact that only a small percentage of the total volume of the reservoirs was below the thermocline support an assumption of full reservoir availability for modeling of aluminum dilution.

Horizontal mixing was assessed by collecting separate samples from three widely separated surface points in Fresh Pond Reservoir on August 19, 2009 (appendix 4). The aluminum concentrations were identical (7 $\mu\text{g/L}$). Despite this evidence of horizontal mixing, reservoir concentrations were assessed in composites of samples from three surface locations.

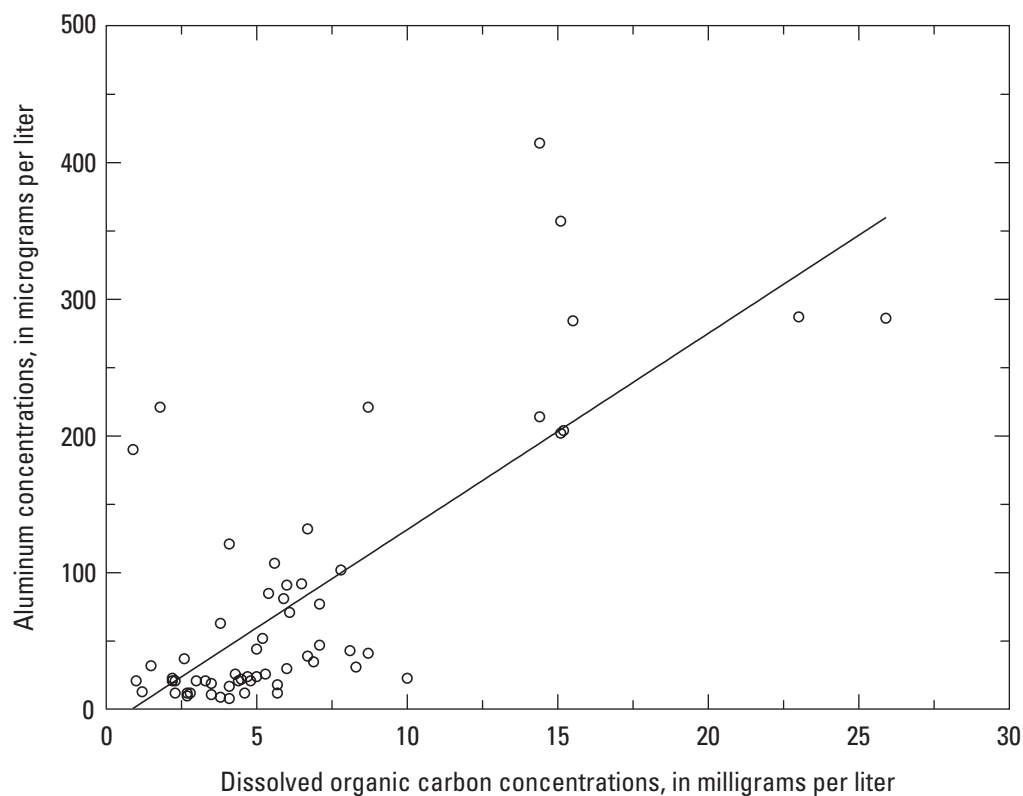


Figure 2. Data and least squares linear regression line for concentrations of total aluminum and dissolved organic carbon in samples from 13 Massachusetts reservoirs and streams, collected from August through November 2009.

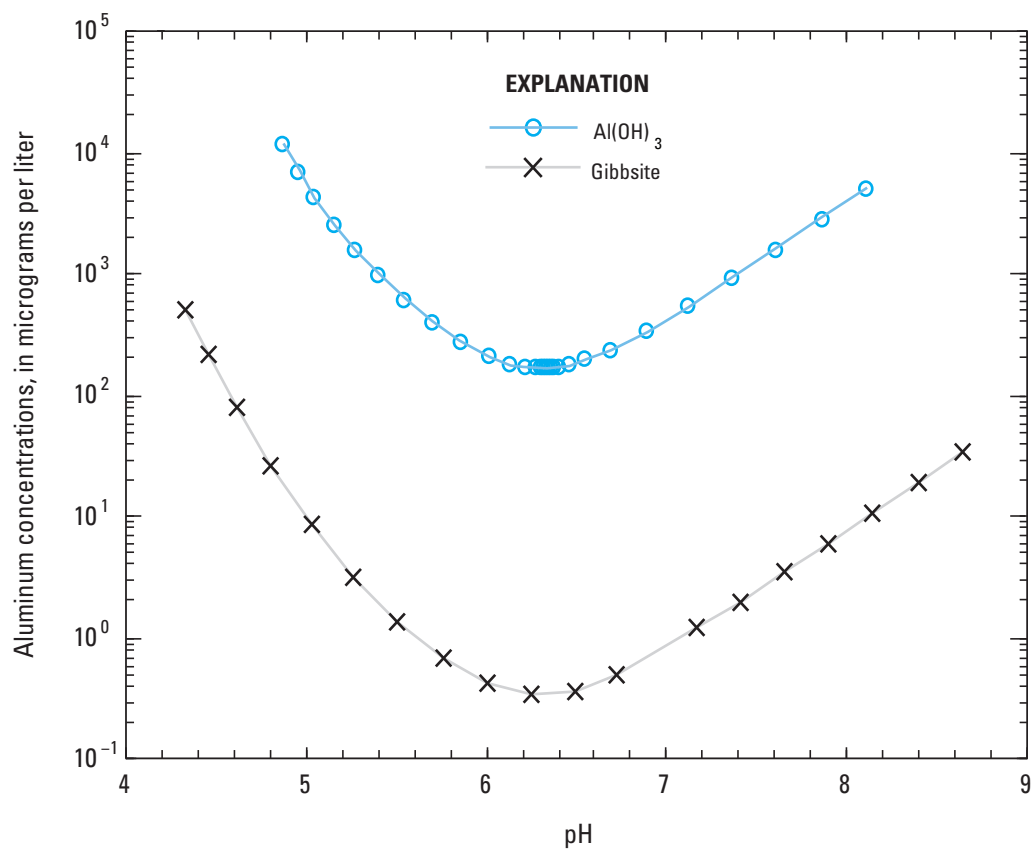


Figure 3. Solubility of aluminum as a function of pH for two solid phases of aluminum, gibbsite and amorphous aluminum hydroxide ($\text{Al}(\text{OH})_3$), determined from the chemical speciation program PHREEQC (Parkhurst and Appelo, 1999).

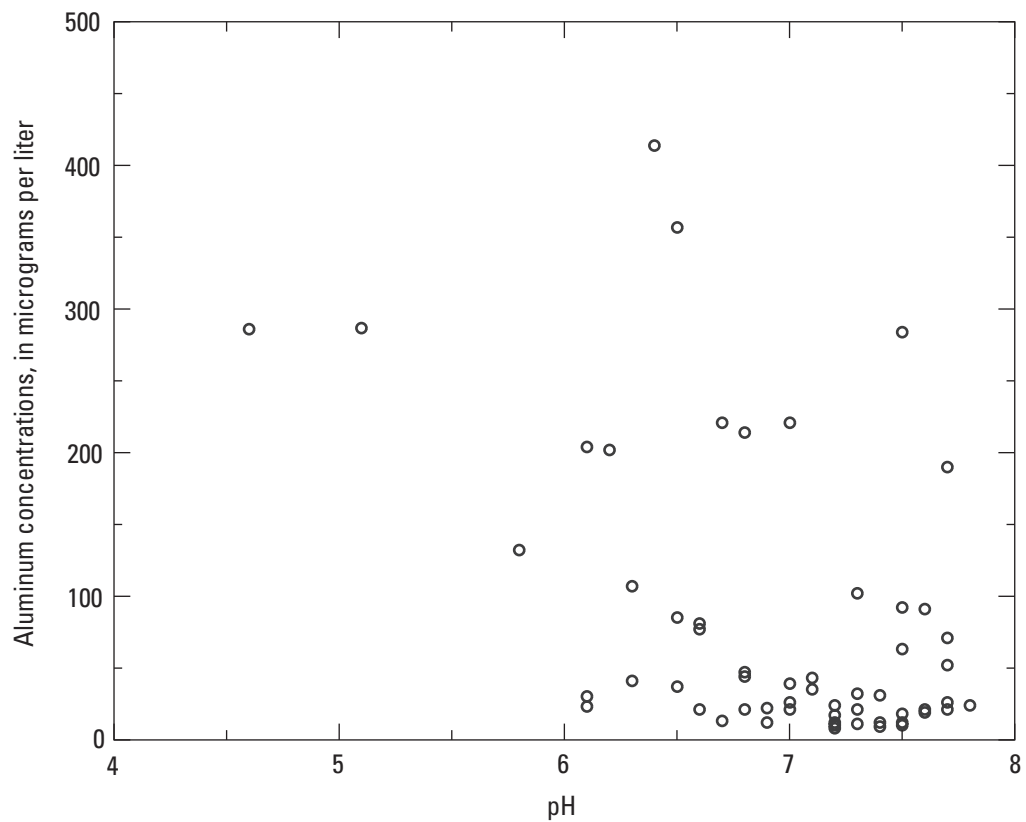


Figure 4. Absence of a relation between total aluminum concentration and pH in samples from 13 Massachusetts reservoirs and streams, measured from August through November 2009.

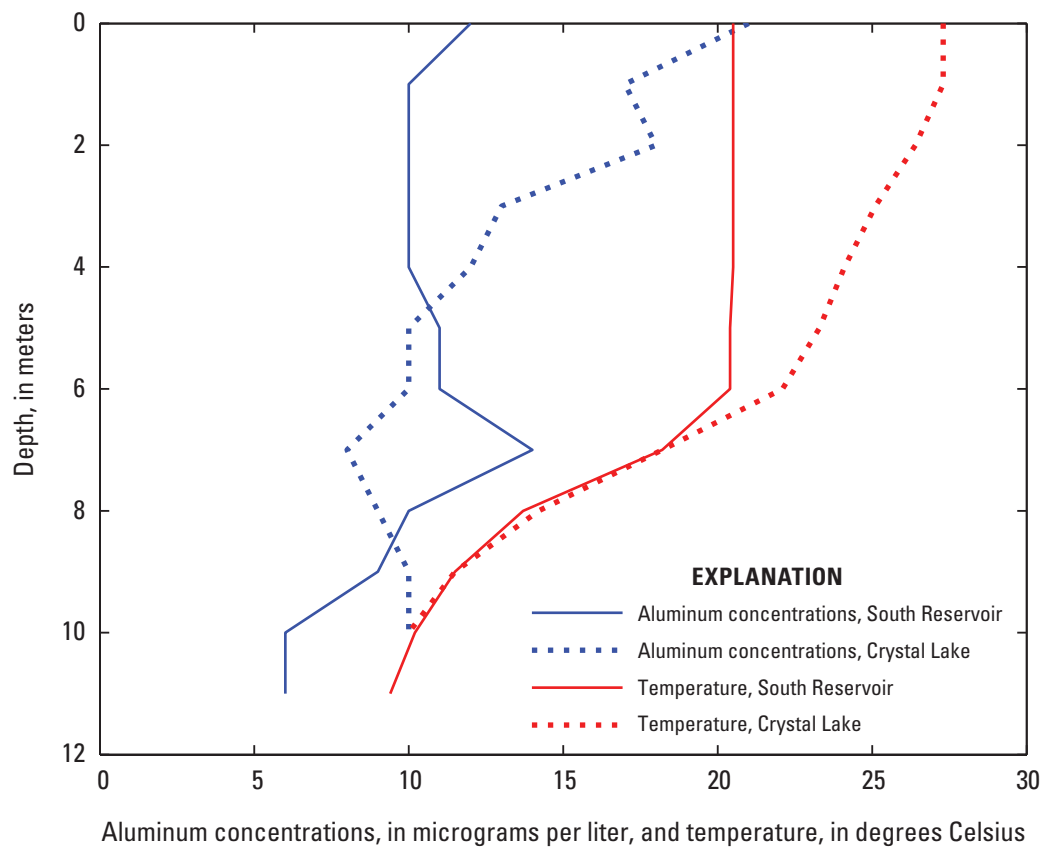


Figure 5. Aluminum concentration and temperature with depth in two Massachusetts reservoirs, sampled on August 20 (Crystal Lake, Gardner) and September 17 (South Reservoir, Winchester), 2009.

Settling-Velocity Results

Aluminum settling velocity was estimated in five reservoirs selected to represent a range of DOC concentrations (table 3). The terms of equation 2 necessary to solve the equation with successive trial settling velocities were obtained as follows. Firm-yield estimates were used for reservoir water withdrawals (Q_w) for the period 1960–2004 (appendix 3). Actual withdrawal patterns (provided by the water supplier) were applied for the period 2005–2009. For other terms of equation 2, the Sustainable-Yield Estimator and Firm-Yield Estimator software were modified to run through the fall of 2009. Averages by reservoir of the three to four measured values for aluminum concentrations of input surface water (C_s) and filter-backwash effluent (C_e) were used in the simulations. The aluminum concentration used for groundwater (C_g) was 10 $\mu\text{g/L}$ (see section “Water-Sample Collection, Processing, and Chemical Analysis”) determined from the USGS QWDATA database.

Input data for one of the settling-velocity reservoirs (Upper Naukeag) could not be obtained because none of the streams were flowing. Also, the aluminum concentrations in the effluent discharge were highly variable, ranging from 183 to 3,390 $\mu\text{g/L}$. Without better control on the concentrations of aluminum discharged, solution of equation 2 for settling velocity was not possible; therefore, Upper Naukeag Lake was excluded from the analysis for settling velocity.

Simulations of reservoir concentrations of aluminum (by solution of equation 2, see section “Calculating Dilution”) for each reservoir were run forward in time from the initial conditions, with differing settling velocities in successive trials for each reservoir. Trials were continued until approximate agreement was reached between measured and simulated concentrations (fig. 6). Initial conditions for each trial used the aluminum concentration measured in the first sampling.

Results from the four reservoirs used indicated that settling velocity does vary as a function of DOC, but that the

relation was overly dependent on one of the reservoirs, Lily Pond (red line, fig. 7). Three of the four average DOC concentrations ranged from 2.7 to 4.5 mg/L , and corresponding best visual-fit settling velocities ranged from 18 to 15 centimeters per day (cm/d). The average DOC concentration in the fourth reservoir, Lily Pond, was 15 mg/L , and the best visual-fit settling velocity was zero. The zero settling velocity indicates that aluminum passage through the reservoir was completely conservative, the DOC apparently maintaining this otherwise insoluble element in solution.

The possibility that settling velocity may also be zero for DOC concentrations lower than 15 mg/L cannot be evaluated using data from the four reservoirs alone because none of the reservoirs selected for settling-velocity determination had intermediate DOC values. However, sampling results from the method-application reservoirs indicated that the DOC concentration in Great Pond, Weymouth, was intermediate (7.8 mg/L). Settling velocity was estimated for Great Pond by extending the streamflow analysis for this pond through 2009. Successive trials were run forward from 1960, and the best-fit settling velocity determined using the aluminum value for the one sampling date available was 1.5 cm/d . The low settling velocity for this reservoir indicates that most of the aluminum was stabilized by DOC, but a small fraction was subject to settling. Linear least-square fit excluding Lily Pond but including Great Pond is shown by the gray and red line (fig. 7). Assuming that the x-axis intercept of this second regression line indicates the point at which all the aluminum is stabilized, the DOC-settling velocity relation between the x intercept and Lily Pond would coincide with the x axis (gray line, fig. 7).

DOC concentrations for all of the remaining method-application reservoirs were less than that of Great Pond, Weymouth, so that the second regression line $S_v \text{ equals } -3.9 * \text{DOC} + 32$ can be used to estimate settling velocities for these reservoirs.

Although the analysis of the conditions in the reservoirs to compute settling velocity required substantial effort, the

Table 3. Data collected to assess aluminum-settling velocities in five reservoirs in Massachusetts.

[Al, aluminum; DOC, dissolved organic carbon; Mgal/d, million gallons per day; $\mu\text{g/L}$, micrograms per liter; mg/L , milligrams per liter; cm/d , centimeters per day; dates in form YYYYMMDD (year, month, day); --, settling velocity could not be calculated]

Reservoir	Period of water-quality record	Average effluent discharge (Q_e) (Mgal/d)	Average discharge concentration (C_e) ($\mu\text{g/L}$)	Groundwater Al concentration (C_g) ($\mu\text{g/L}$)	Average surface-water concentration (C_s) ($\mu\text{g/L}$)	Average DOC (mg/L)	Final settling velocity (cm/d)
Lily Pond	20090924 to 20091119	0.11	804	10	206	15	0
Fresh Pond	20090819 to 20091118	0.44	1,450	10	17	3.6	20
Crystal Lake	20090820 to 20091110	0.59	1,900	10	74	2.7	25
Haggetts Pond	20090818 to 20091118	0.63	3,810	10	72	4.5	17
Upper Naukeag Lake ¹	20090826 to 20091110	0.12	1,280	10	17	2.3	--

¹ Because discharge concentrations were highly variable and no surface-water samples were collected, the average surface-water concentration was set to equal the value for Fresh Pond, and a final settling velocity could not be calculated.

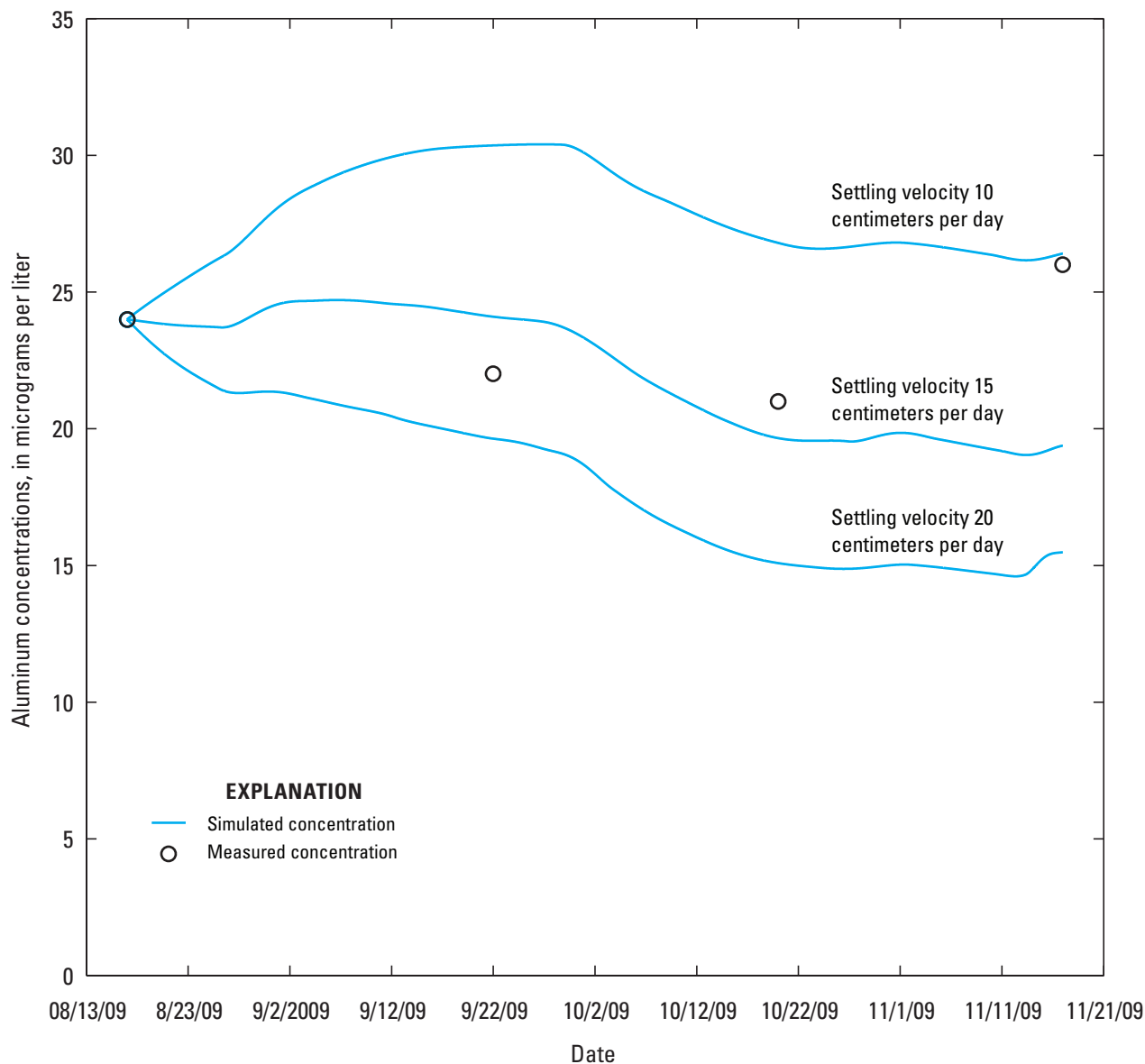


Figure 6. Measured and simulated aluminum concentrations for an example reservoir, Haggetts Pond, for three trial settling velocities of aluminum.

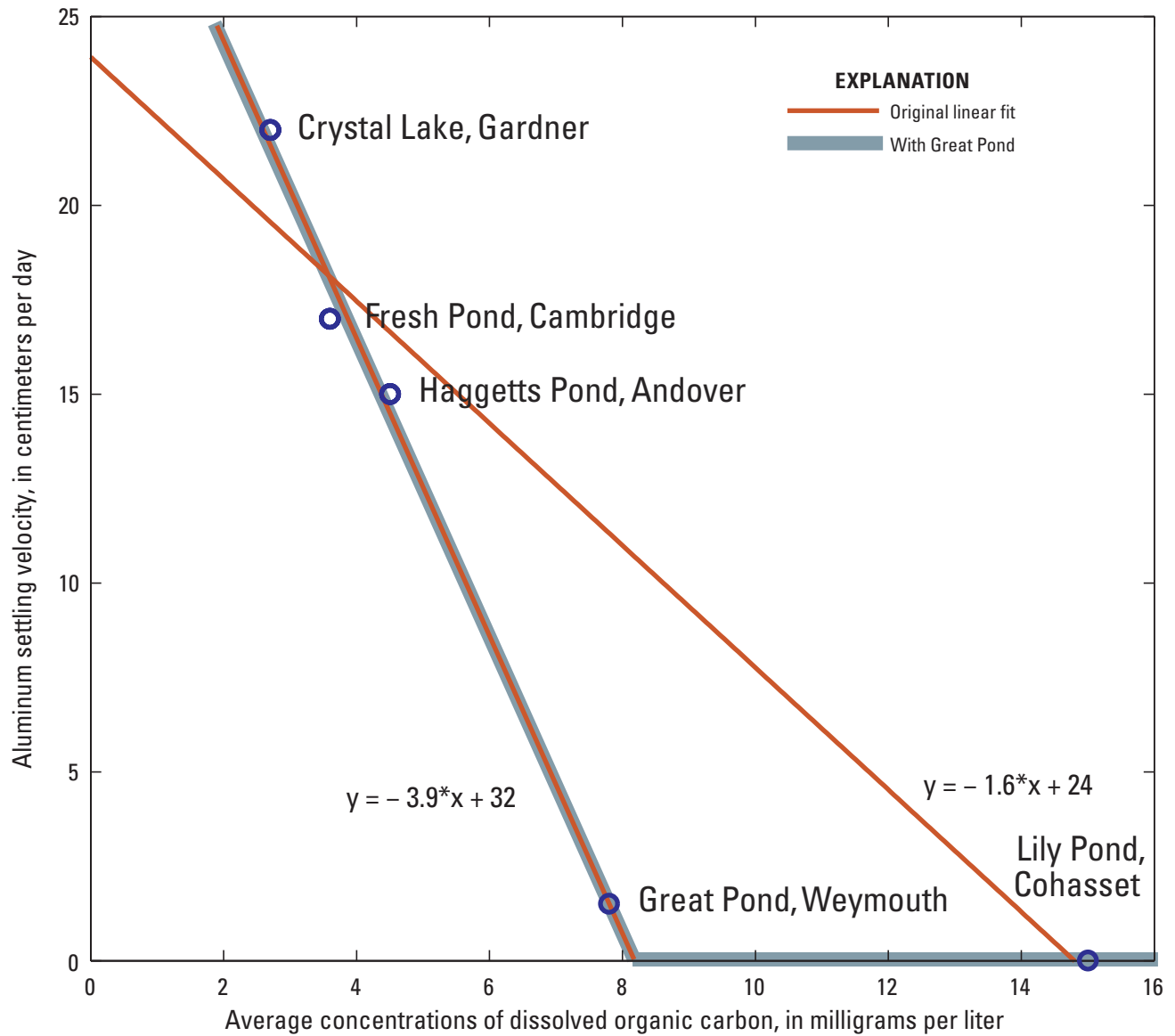


Figure 7. Relation between aluminum settling velocity and average concentrations of dissolved organic carbon. All results were from fitting simulation results to four sample measurements, except for the results for Great Pond, which were fit to one sample measurement. Equations are linear least-square fits of data.

number of reservoirs and amount of data were not sufficient to define the DOC-settling velocity relation with certainty. Uninvestigated are any seasonal effects that may apply. The relation was used tentatively in this study and its appropriateness considered in the comparison of predicted versus measured results for all the reservoirs.

Aluminum Simulation Results

Simulations of aluminum concentrations in reservoir water columns are integral to determining the dilution factors, which are simply the ratios of aluminum concentration in the filter-backwash effluent to that of the reservoir. As an example, reservoir concentrations were calculated for Quittacas Pond, New Bedford, by solving equation 2, with the settling velocity determined as in the previous section. Daily values for aluminum concentration were computed for the period of record, October 1960 through September 2004. The simulation results typically show the aluminum concentration varying substantially with time because of differing input flows to the reservoir and include concentrations above the chronic standard of 87 $\mu\text{g/L}$ (fig. 8).

The settling velocity was calibrated using data from 5 of the 13 reservoirs, so the modeling approach can be verified to a degree by comparing predicted and measured aluminum concentrations for the remaining 8 application reservoirs. Because the Massachusetts Sustainable Yield Estimator data extended only through 2004, and our measurements were made in the fall of 2009, a time translation was necessary to make the comparison. Flows were relatively low in August and September of both 2004 and 2009, so that similar dilution by flow might apply. To make the comparisons, averaged simulated data from August and September 2004 were compared to the one measured data point in fall of 2009 for each reservoir (fig. 9). Values below 150 $\mu\text{g/L}$ corresponded well, as indicated by the high R-squared value.

There was one outlier site, the unnamed pond at Clinton, Mass., which had a measured aluminum value of 221 $\mu\text{g/L}$ and simulated aluminum value of 1,000 $\mu\text{g/L}$. This site also had uncertain inflow. The effluent discharge was to a small water body immediately below the large dam of the Wachusett Reservoir. Substantial flow by leakage from the upper reservoir likely occurred that was not accounted for in the Massachusetts Sustainable Yield Estimator analysis. The leakage flow could have diluted the aluminum concentration that was measured.

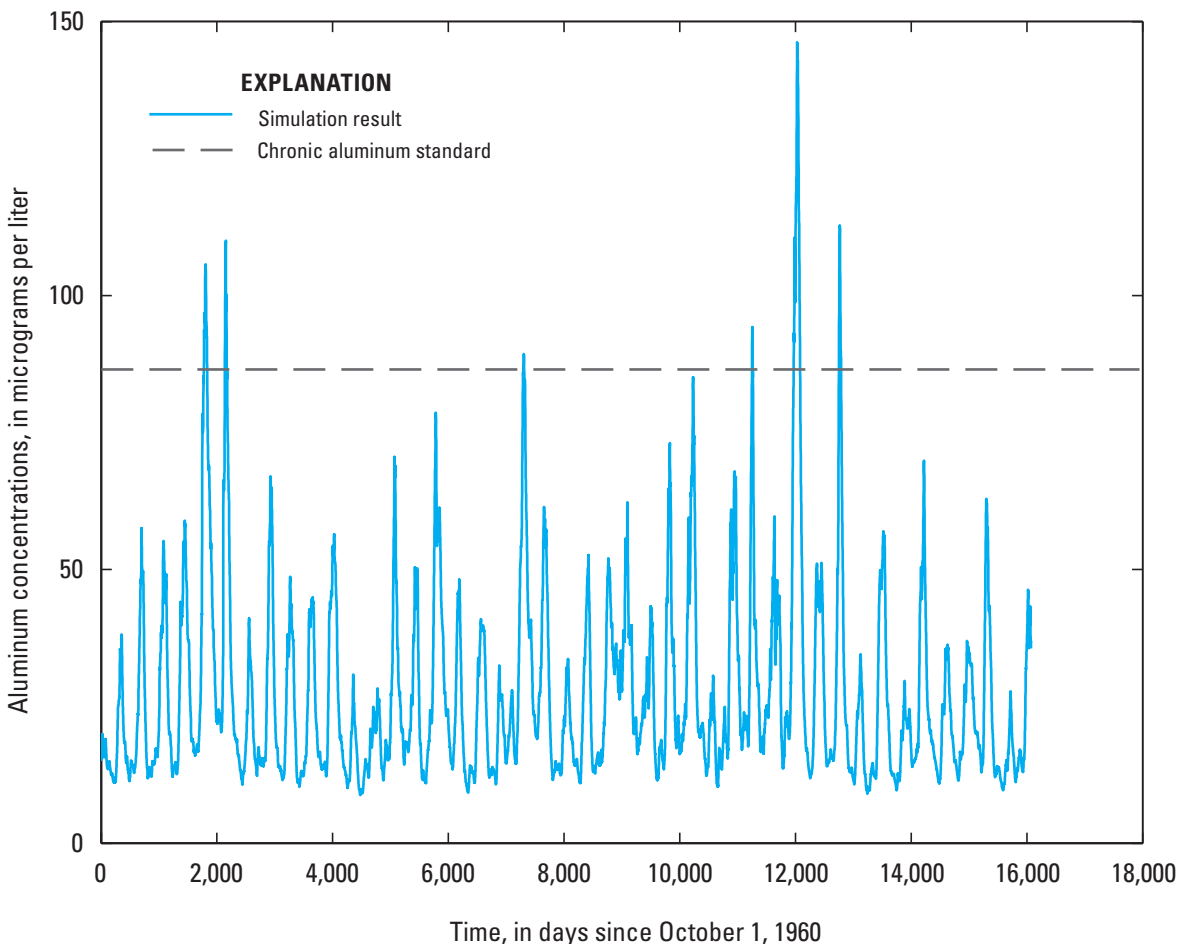


Figure 8. Simulated aluminum concentrations for an example reservoir, Quittacas Pond in New Bedford, from October 1960 to September 2004, with the chronic standard for aluminum toxicity (87 $\mu\text{g/L}$) indicated.

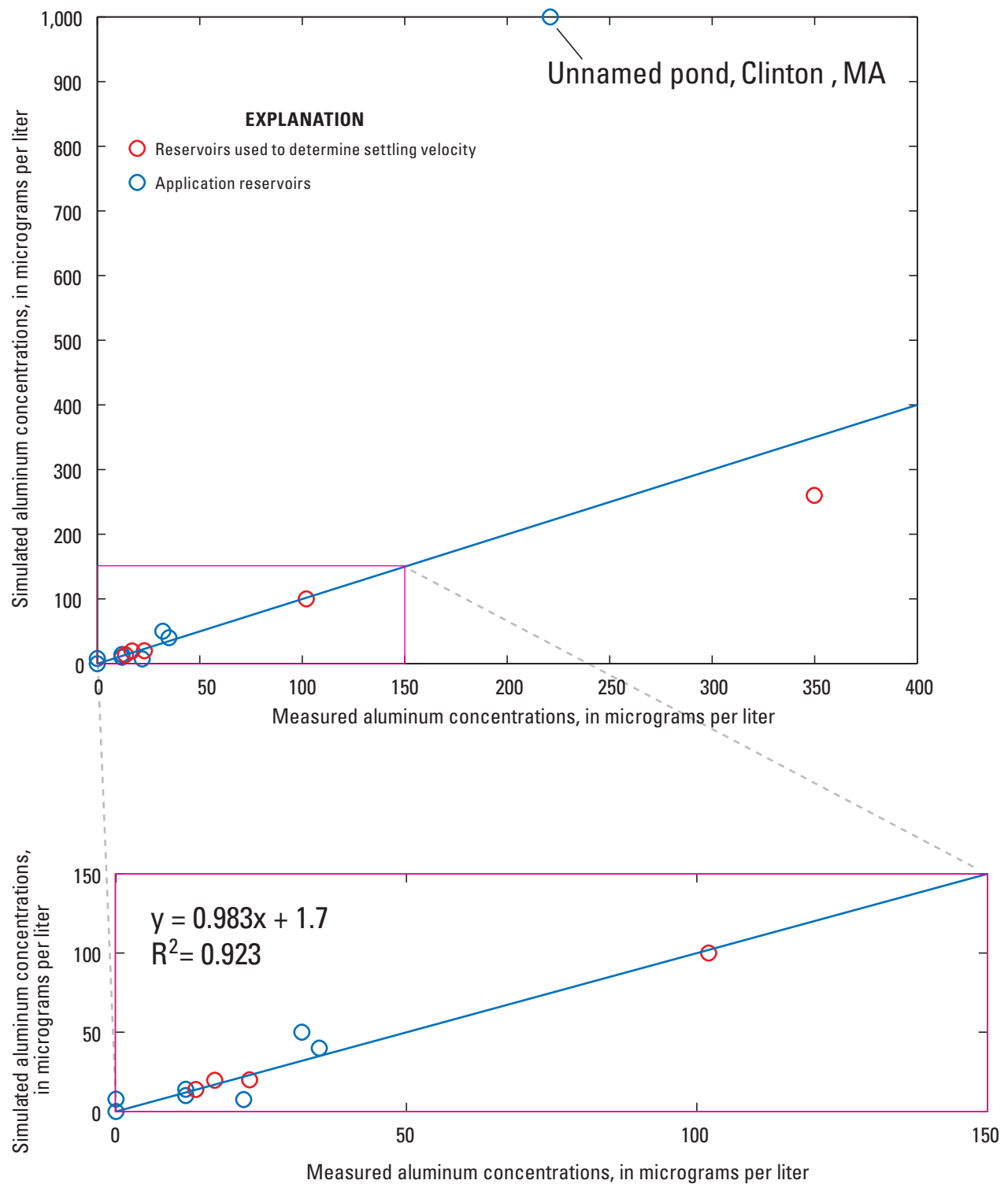


Figure 9. Measured versus simulated aluminum concentrations and equivalence line for fall 2009. Red symbols are for reservoirs used to determine settling velocity. Blue symbols are for application reservoirs. Equation represents linear least-squares fit of data for the aluminum-concentration range of 0–150 micrograms per liter.

Dilution-Factor Results

As computed by the ratio of discharge concentration to reservoir concentration (equation 3), DF values are variable and can range over several orders of magnitude (fig. 10).

Low-Flow Dilution

As explained in the section named “Investigative Design,” DF values that represent the least amount of dilution are of interest for the purpose of setting discharge permits that are protective of the resource. In determining the 7DF10, the lowest 7-day average for each year is selected (fig. 11). Next, the annual minimum 7-day-average dilution factors are fit to a known distribution, so that the value with a 10-year recurrence interval (7DF10) can be selected (fig. 12). The 10-year recurrence interval corresponds to an annual nonexceedence probability of 10 percent. For simulation data from Quittacas Pond, the 7DF10 is 4.80 (fig. 12).

Finding the Maximum Permissible Aluminum Discharge

The goal of permitting is to protect water supplies from concentrations of aluminum toxic to aquatic life. To achieve that, it is important to know the maximum permitted discharge that would result, after low-flow dilution, in a reservoir concentration that just meets the standard. Because the DF is the ratio of concentrations of aluminum in the effluent to concentrations of aluminum in the reservoir water, the reservoir aluminum concentration at the 7DF10 can be computed. That concentration for Quittacas Pond is $438/4.80$ equals $91.3 \mu\text{g/L}$. The chronic criterion concentration for aluminum is $87 \mu\text{g/L}$; therefore, this water supply system is just over the standard (by $4.3 \mu\text{g/L}$).

With discharges to streams, equation 3 can be used with the 7DF10 to determine the highest allowable aluminum discharge, which would be the value of C_e when C is $87 \mu\text{g/L}$, the chronic limit. Determining how much decrease or increase

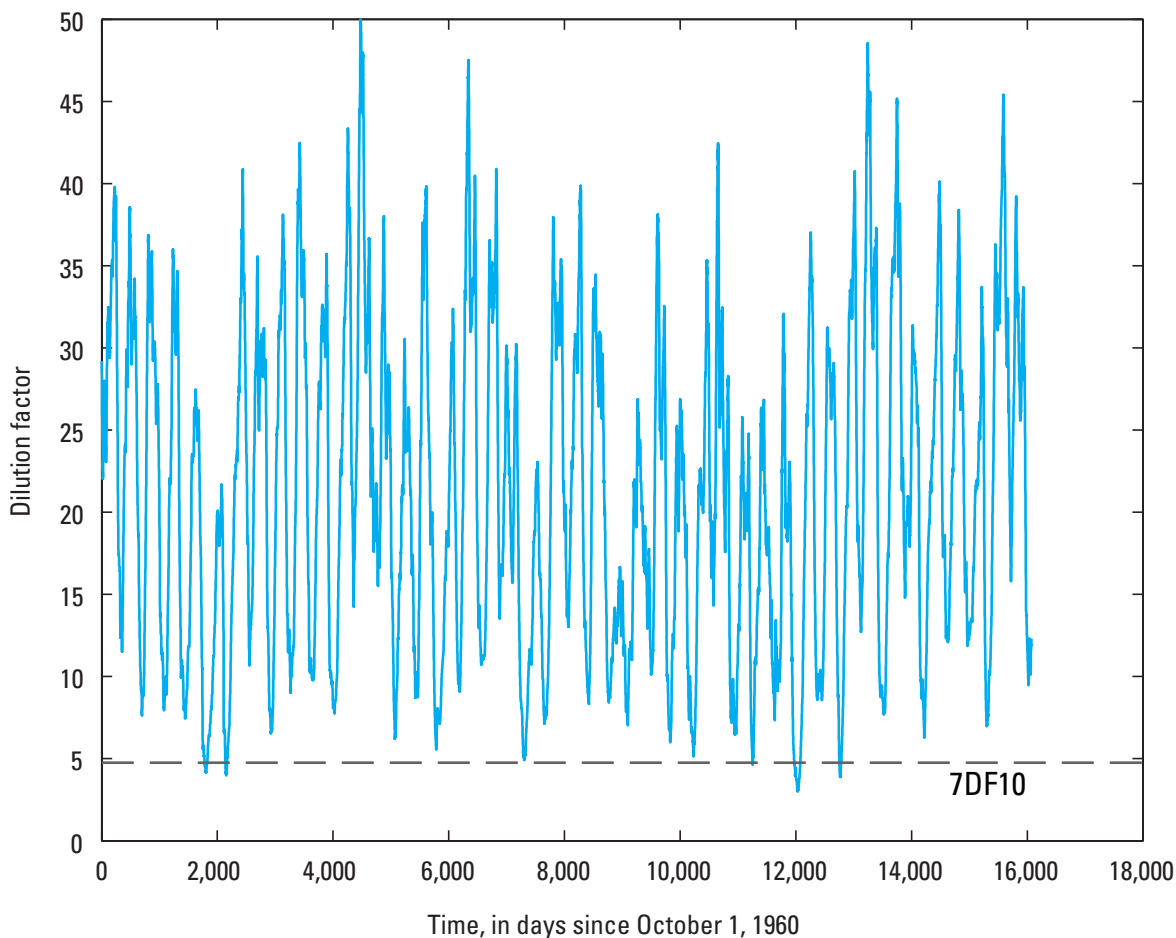


Figure 10. Aluminum-dilution factors and the 7DF10 for filter-backwash effluent for an example reservoir, Quittacas Pond in New Bedford, with an effluent concentration of $438 \mu\text{g/L}$, measured during fall 2009.

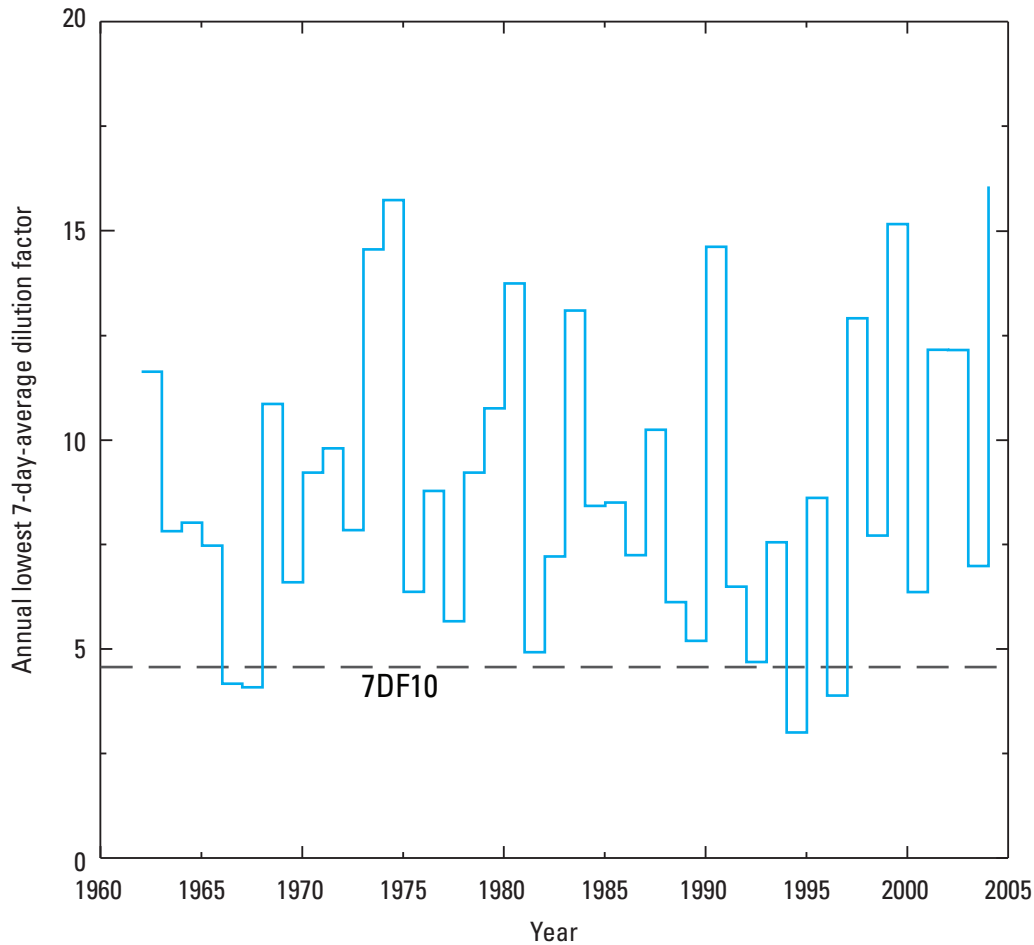


Figure 11. Annual lowest 7-day-average dilution factors based on simulation data for Quittacas Pond, New Bedford, and the level of the 7DF10 (4.80, from fig. 12).

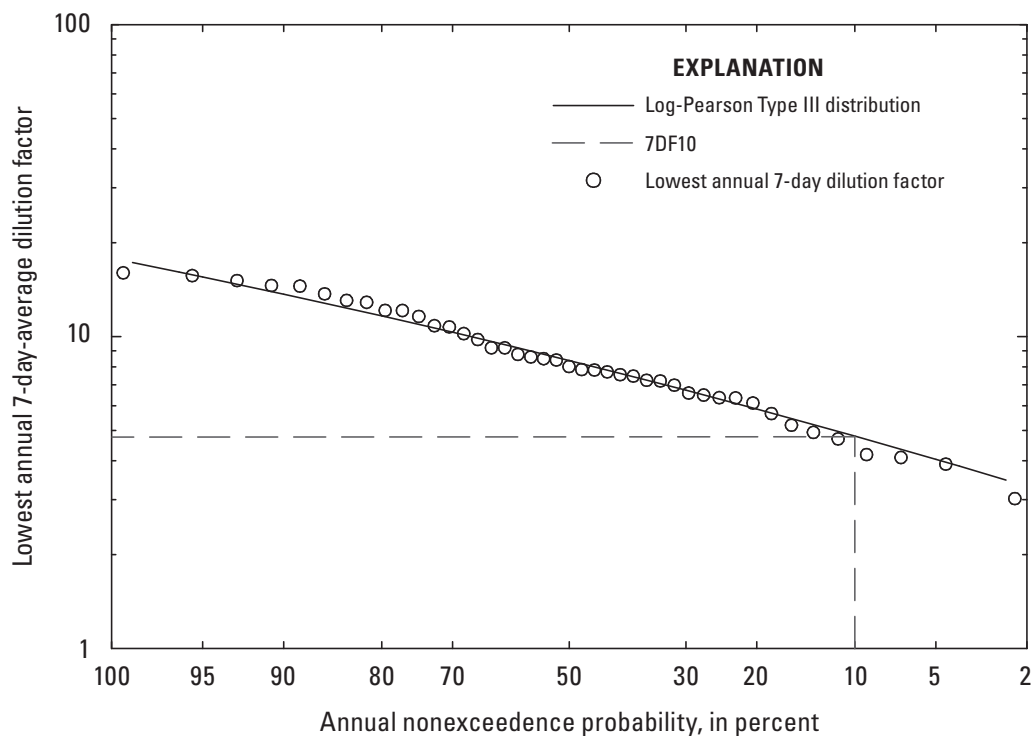


Figure 12. Fit of lowest annual 7-day-average dilution data to log Pearson type III distribution for Quittacas Pond, New Bedford. The lowest annual 7-day-average dilution factor with a 10-year recurrence interval, which is the 7DF10 value, corresponds to the annual nonexceedence probability of 10 percent, as indicated by the dashed line, and is equal to 4.80.

is possible for reservoirs is complex, however, because the 7DF10 may change when the discharge is changed.

For example, when C_e of Quittacus Pond is changed from 438 to 200 $\mu\text{g/L}$, the 7-day-average values decrease (fig. 13). When fit to the log Pearson type III distribution, the 7DF10 value is less also (fig. 14). The new 7DF10 is 2.27, which corresponds to a reservoir concentration of $200/2.27$ equals 88 $\mu\text{g/L}$, approximately equal to the chronic standard.

By comparison with the range of reservoir DOC concentrations measured in this study (1.5 to 15.5 mg/L , with a 3.4 mg/L median), Quittacus Pond has a relatively high DOC concentration, 6.9 mg/L and thus high aluminum concentrations and low DF s, and it therefore requires a lower aluminum discharge than currently used to meet the standard. For other reservoirs and surface-water supplies with lower DOC concentrations, effluent concentrations after low-flow dilution would be expected to result in reservoir concentrations that were lower than the chronic standard. For example, the 7DF10 under the present effluent discharge for South Reservoir is 105, and the associated aluminum concentration in the reservoir is 12.5 $\mu\text{g/L}$. This water supplier could increase the aluminum discharge and still be in compliance.

Generally, as concentration of effluent discharged to a reservoir is increased, the 7DF10 increases also. However, the 7DF10 eventually converges on one value in successive model runs (fig. 15).

Multiple 7DF10- C_e pairs are thus required to find the one that corresponds to the reservoir concentration that is at the chronic standard. This computationally demanding requirement is lessened for ranges of C_e for which the variation of 7DF10 with C_e is approximately linear. In those ranges, the plot of C versus C_e will also be linear, and the value of C_e that will correspond to the chronic standard being met in the reser-

voir can be determined by interpolation within these linear-response zones (fig. 16).

Comparison of aluminum concentrations at a permitted discharge with C_e equals 200 $\mu\text{g/L}$ and the current discharge with C_e equals 436 $\mu\text{g/L}$ are shown for Quittacus Pond (fig. 17). At C_e equals 200 $\mu\text{g/L}$, the simulated concentrations are slightly less than at C_e equals 436 $\mu\text{g/L}$ and extend above the 87 $\mu\text{g/L}$ limit five times, close to the number that would be expected for a 10-year recurrence interval in a 44-year record (four).

Once the maximum concentration in effluent that meets the water-quality standard in the reservoir has been determined, the value can be converted to a maximum aluminum load by multiplying by effluent discharge (table 4).

The key factors that influence the amount of aluminum that can be discharged are summarized in table 4. They include the current concentrations of aluminum and DOC measured in the reservoir, estimated settling velocity of aluminum, current effluent discharge volume, the 7DF10 that applies to current effluent discharge and the aluminum concentration in the effluent, and the 7DF10 and the effluent concentration that would apply if the effluent concentration were increased to the highest value that still allows the reservoir standard of 87 $\mu\text{g/L}$ to be met. The ratio of the highest permissible effluent concentration and the original effluent concentration indicates the factor by which the concentration could be increased and still meet the standard (for ratios greater than 1) or the factor by which concentration must be decreased to meet the standard (for ratios less than 1). Aluminum flux in the discharge is the calculated amount that is permissible for the reservoir standard to be met. The calculated permissible aluminum fluxes ranged from 0 to 28 kilograms of aluminum per day.

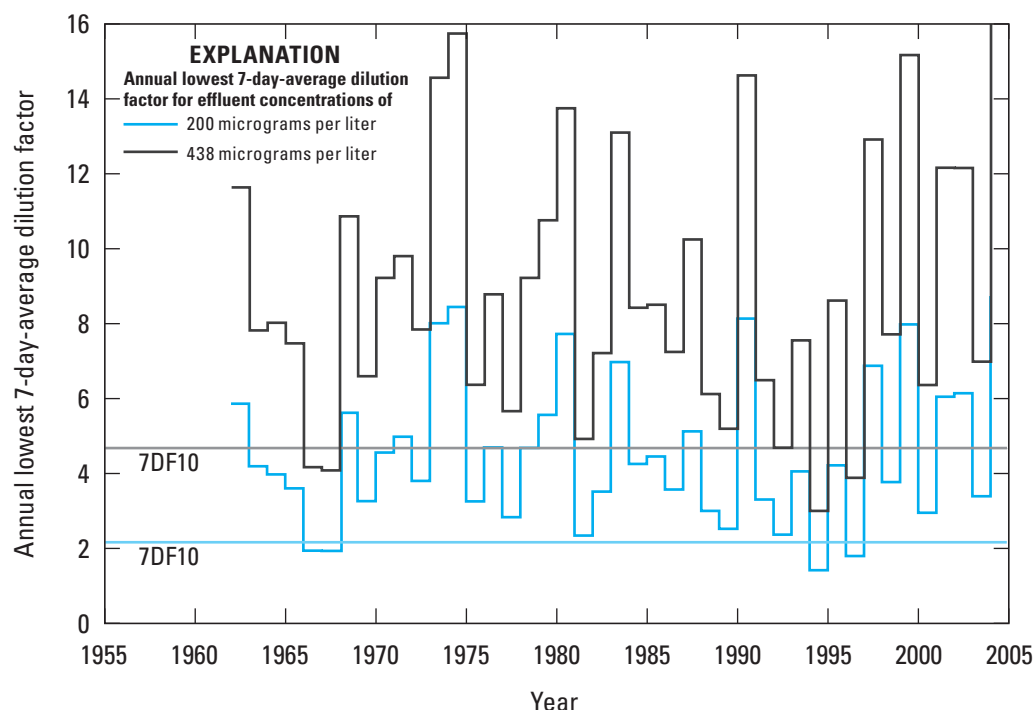


Figure 13. Annual lowest 7-day-average dilution factors based on simulation data for Quittacus Pond, New Bedford. Blue represents filter-backwash-effluent aluminum concentration of 200 $\mu\text{g/L}$ and black filter-backwash-effluent aluminum concentration of 438 $\mu\text{g/L}$.

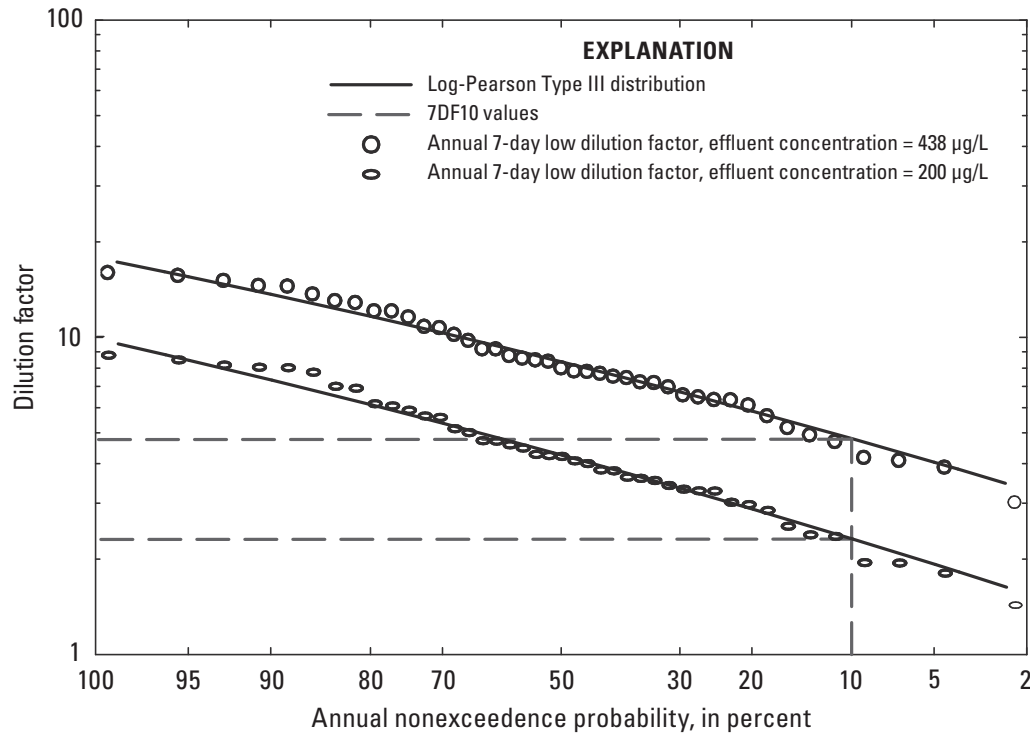


Figure 14. Fit of lowest annual 7-day dilution data to log Pearson type III distribution for Quittacas Pond, New Bedford, for two levels of filter-backwash-effluent aluminum concentration 438 and 200 µg/L. The values for the 10-year recurrence interval, which are the 7DF10 values, are 4.80 and 2.27, respectively.

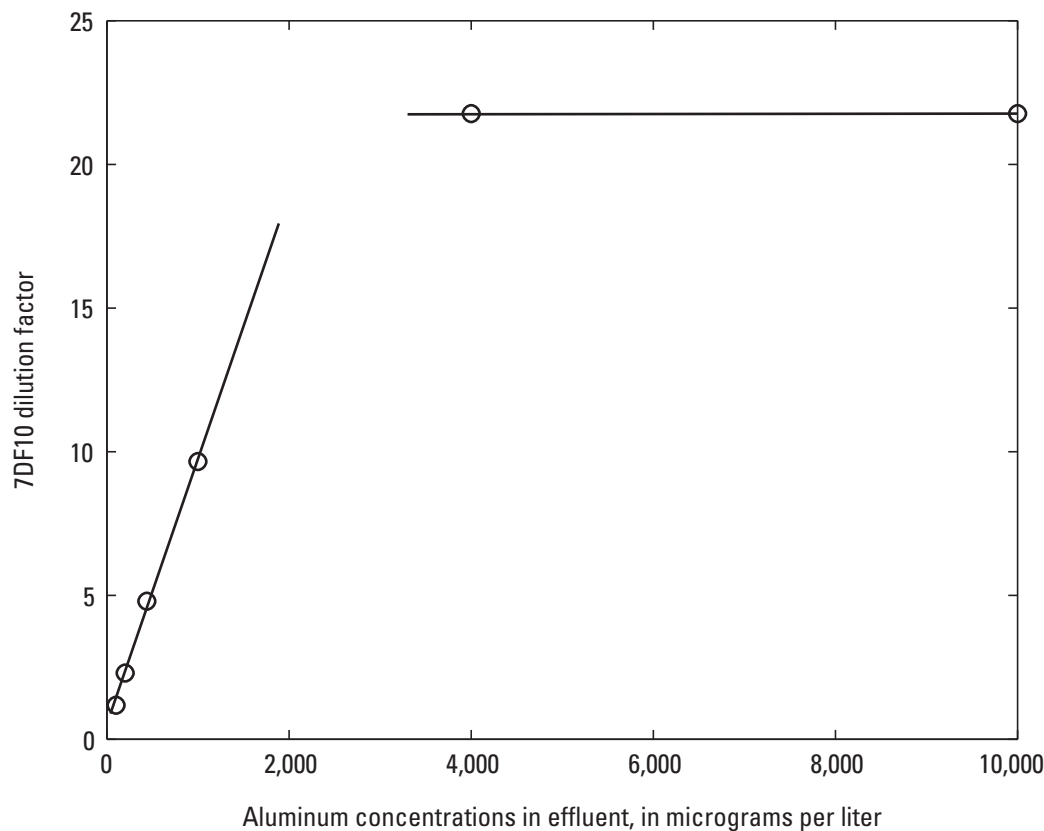


Figure 15. 7DF10 values as a function of aluminum concentration in filter-backwash effluent for Quittacas Pond, New Bedford. Two nearly linear regions of the relation are identified.

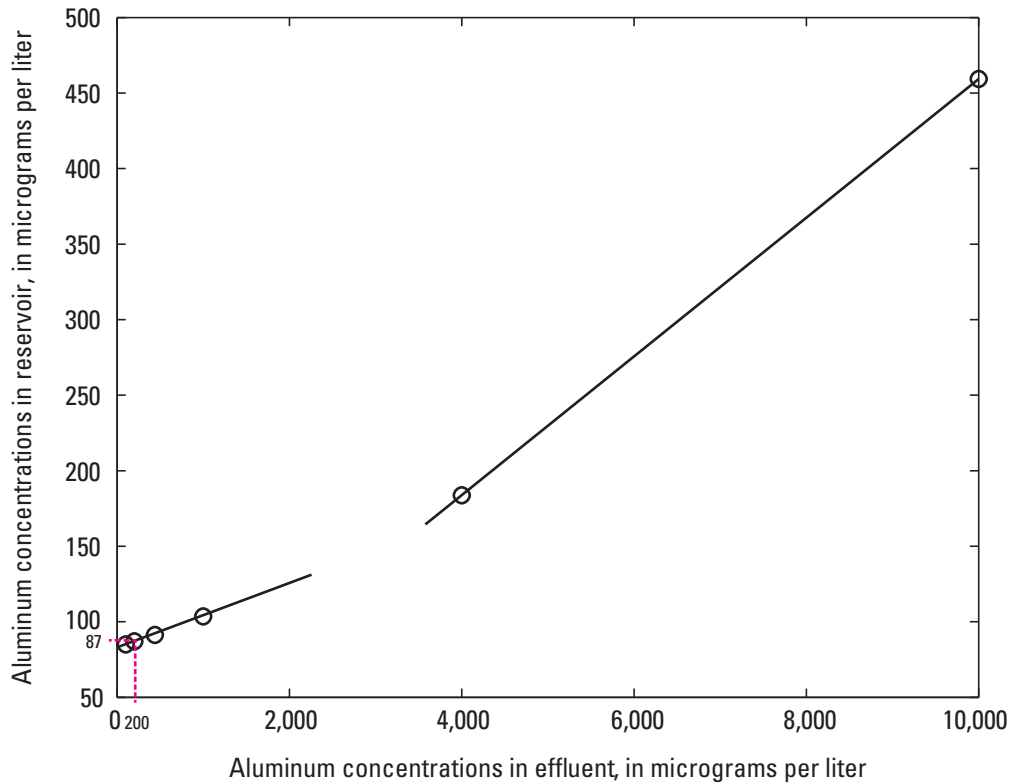


Figure 16. Relation between filter-backwash-effluent concentration of aluminum and the reservoir concentration at the 7DF10 for Quittacas Pond, New Bedford. The short dashed horizontal red line indicates the chronic standard of 87 $\mu\text{g/L}$ in the reservoir, and the dashed vertical red line shows the result of 200 $\mu\text{g/L}$ for the effluent (C_e) at the 7DF10.

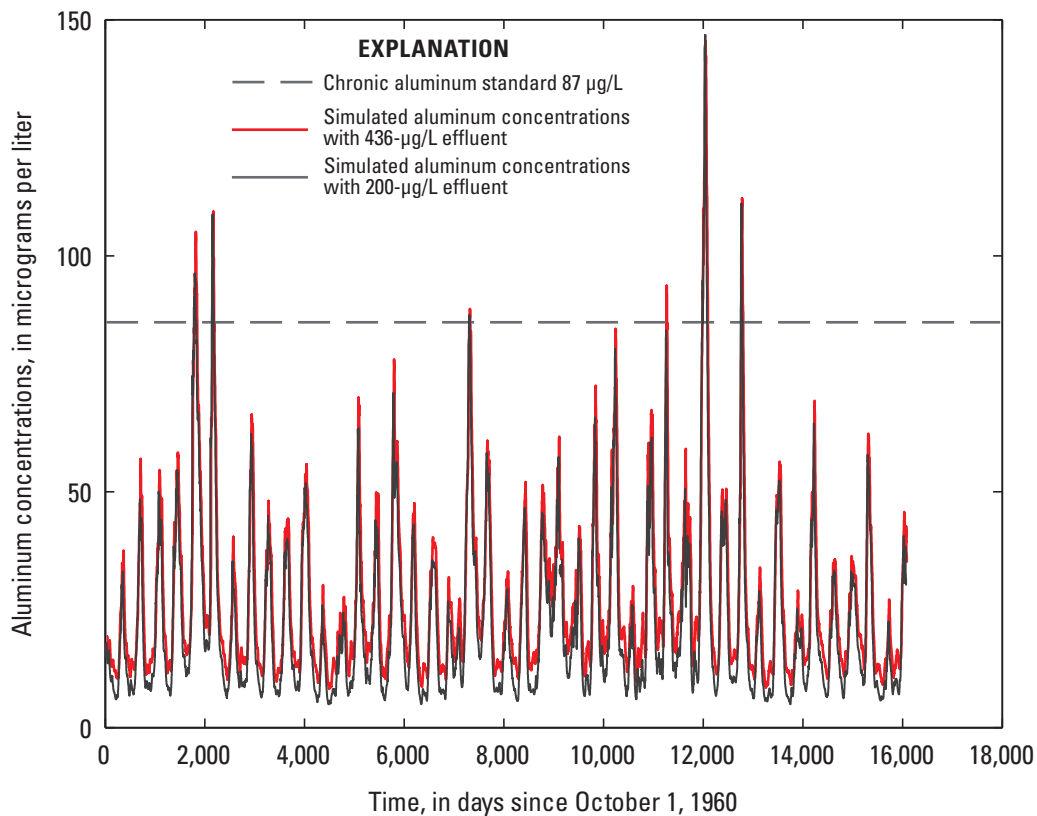


Figure 17. Simulated aluminum concentrations in Quittacas Pond, New Bedford, with concentrations of aluminum in the discharge of 436 $\mu\text{g/L}$ (red) and 200 $\mu\text{g/L}$ (black). The horizontal line is the standard for chronic aluminum toxicity, 87 $\mu\text{g/L}$.

Table 4. Highest 7DF10 values, filter-backwash effluent concentrations, and fluxes that meet standards for aluminum discharge in 13 reservoirs of Massachusetts town water supplies.

[m², square meters; Mgal, million gallons; Mgal/d, million gallons per day; Al, aluminum; µg/L, micrograms per liter; DOC, dissolved organic carbon; mg/L, milligrams per liter; cm/d, centimeters per day; 7DF10, lowest annual 7-day average dilution factor with a recurrence interval of 10 years; C_e , total aluminum concentration in the filter-backwash effluent; kg, kilograms; WTP, water-treatment plant; WTF, water-treatment facility; --, no data; \leq , less than or equal to]

Facility and receiving water	Area (A, in m ²) and volume (V, in Mgal)	Average stream discharge (Q_s , in Mgal/d) and Al concentration (C_s , in µg/L)	Reservoir averages—DOC (mg/L) and Al (µg/L)	Settling velocity (cm/d)	Current effluent discharge (Mgal/d)	7DF10 and associated C_e value at the current discharge	Highest 7DF10 and C_e that meet standard	C_e ratio—new:old ¹	Permissible aluminum flux (kg per day)
Andover WTP Haggetts Pond	A = 916,000 V = 856	Q_s = 6.12 C_s = 72	DOC = 4.5 Al = 23	14.5	0.63	81 3,810	135 11,700	3.1	28
Ashburnham/Winchendon WTP Upper Naukeag Lake	A = 1,270,000 V = 1,572	Q_s = 2.45 C_s = 72	DOC = 2.3 Al = 25.5	23	0.12	62 3,390	624 54,300	16	24.6
Cambridge WTP Fresh Pond Reservoir	A = 645,000 V = 1,500	Q_s = 15.9 C_s = 17	DOC = 3.6 Al = 17	18	0.44	66 1,450	87 7,500	5.2	13
Clinton WTP Unnamed pond	A = 16,400 V = 4.58	Q_s = 0.608 C_s = 13	DOC = 1.8 Al = 221	25	0.33	3.7 3,610	3.2 276	0.076	0.34
Clinton WTP run #2 with increased groundwater flow						15.4 3,610	14.4 1,250	0.35	1.57
Cohasset WTP Lily Pond	A = 206,000 V = 73.5	Q_s = 3.07 C_s = 206	DOC = 15 Al = 351	0	0.11	2.2 804	--	Above standard even when C_e = 0	--
Gardner WTF Crystal Lake	A = 616,000 V = 746	Q_s = 1.79 C_s = 74	DOC = 2.7 Al = 13.8	21.5	0.59	49 1,900	90 7,500	4	17
Manchester-by-the-Sea and Hamilton WTP Gravelly Pond	A = 203,000 V = 327	Q_s = 0.24 C_s = 10	DOC = 3 Al \leq 6	20.3	0.02	51 107	139 12,200	113	0.94

Table 4. Highest 7DF10 values, filter-backwash effluent concentrations, and fluxes that meet standards for aluminum discharge in 13 reservoirs of Massachusetts town water supplies.—Continued

[m², square meters; Mgal, million gallons; Mgal/d, million gallons per day; Al, aluminum; µg/L, micrograms per liter; DOC, dissolved organic carbon; mg/L, milligrams per liter; cm/d, centimeters per day; 7DF10, lowest annual 7-day average dilution factor with a recurrence interval of 10 years; C_e , total aluminum concentration in the filter-backwash effluent; kg, kilograms; WTP, water-treatment plant; WTE, water-treatment facility; --, no data; ≤, less than or equal to]

Facility and receiving water	Area (A, in m ²) and volume (V, in Mgal)	Average stream discharge (Q_s , in Mgal/d) and Al concentration (C_s , in µg/L)	Reservoir averages—DOC (mg/L) and Al (µg/L)	Settling velocity (cm/d)	Current effluent discharge (Mgal/d)	7DF10 and associated C_e value at the current discharge	Highest 7DF10 and C_e that meet standard	C_e ratio—new:old ¹	Permissible aluminum flux (kg per day)
New Bedford Little Quittacas Pond	A = 1,230,000 V = 606	Q_s = 1.97 C_s = 147	DOC = 6.9 Al = 35	5.1	0.32	4.8 438	52 200	0.45	0.24
Northampton WTP Mountain Street Reservoir	A = 283,000 V = 327	Q_s = 1.07 C_s = 190	DOC = 1.7 Al ≤ 5	25.4	0.27	10.7 233	11 966	4.3	1.97
Salem and Beverly Water Supply Board Wenham Lake Reservoir	A = 1,030,000 V = 1,930	Q_s = 8.21 C_s = 83	DOC = 4.6 Al = 12	14.1	0.41	17 672	45 3,900	5.8	6.14
Weymouth WTP Great Pond	A = 2,080,000 V = 1,160	Q_s = 4.24 C_s = 286	DOC = 7.8 Al = 102	1.6	0.15	1.8 442	--	Above standard even when C_e = 0	--
Winchester WTP South Reservoir	A = 323,000 V = 669	Q_s = 0.545 C_s = 10	DOC = 2.3 Al = 12	23	0.12	115 1,320	128 11,200	8.5	5.07
Worcester WTP Holden Reservoir #2	A = 214,000 V = 244	Q_s = 1.08 C_s = 21	DOC = 1.5 Al = 32	26.2	1	14.5 748	14.5 1,260	1.7	4.8

¹ "New" means the C_e value that ensures just meeting the standard.

Discussion of Method Applications

Permitted Discharges

Results from the reservoirs simulated indicate that most suppliers could be discharging more aluminum in filter backwash than they are now and still meet the chronic standard for aluminum. Four reservoirs, however, are at or over the standard at the present rate of aluminum discharge. Three of these are reservoirs with high DOC concentrations in the water column and in tributaries (table 4, appendix 4). Several tributaries with high DOC concentrations had aluminum concentrations that were over the chronic standard for aluminum. Concentrations of aluminum in reservoirs receiving discharge from these tributaries would be greater than the chronic standard even without additional aluminum added from backwash discharges.

The high-aluminum, low-DOC reservoir exception was a small pond at the Clinton WTP, not part of the reservoir supply, which received a large aluminum discharge. In this case, removal by settling probably occurs, but is overwhelmed by the amount of aluminum discharged compared to the small area of the pond in which settling could occur. There is further discussion of this reservoir below.

Limits to the Applicability of the Method

The model did not apply well to the small pond receiving aluminum discharge at Clinton, Mass., the reservoir that plots well off the verification curve (fig. 9). The Firm Yield Estimator model likely was not suited for estimating the inflow to this reservoir because of substantial groundwater flow. Located just below the Wachusett Reservoir Dam, this pond likely also received substantial dilution water from leakage through the dam that was not accounted for by the Firm Yield Estimator model. Increasing the flow through the pond from groundwater (run # 2, table 4) by 4.5 million gallons per day (Mgal/d) brought the simulated concentration to the level of the measured concentration of 221 $\mu\text{g/L}$. With the extra flow, a greater amount of aluminum could be discharged than was the case in the original simulation. The second permissible aluminum-concentration result is still less than the value currently discharged, however. The increased flow used in the second run has not been verified, and thus accurate regulation at this site would require more flow investigation.

Environmental Consequences of Aluminum Discharges

Potential violations of aluminum concentration standards are primarily associated with reservoirs that have high

concentrations of DOC. Although the aluminum concentrations in these reservoirs may be above standards, the binding with DOC may keep the aluminum from becoming toxic to aquatic life (Gundersen and others, 1994). Assessment of toxicity would require site-specific investigations of the effect of the water matrix on availability of aluminum to aquatic life.

Summary

A method was developed to assess dilution of the aluminum found in filter-backwash effluent discharged to reservoirs from water-treatment plants. The method was needed to facilitate discharge-permit writing by the Massachusetts Department of Environmental Protection to ensure compliance with water-quality standards for aquatic life. The method uses a mass-balance equation for aluminum in reservoirs that considers sources of aluminum from groundwater, surface water, and filter-backwash effluents and losses due to sedimentation, water withdrawal, and spill discharge from the reservoir. The method was applied to 13 water-supply reservoirs in Massachusetts.

A main result of this investigation was the determination that dilution for aluminum discharged to reservoirs depends on the concentration discharged, unlike the case generally assumed for discharge to streams. This means that a dilution factor (*DF*) value determined for low-flow conditions at one effluent concentration cannot be used to determine the effluent concentration that would just meet the standard. A series of determinations of dilution at multiple effluent concentrations can lead to a dilution-factor/discharge-concentration pair that will meet the standard. Although *DF* evaluation for reservoirs was different from that for streams, the method developed here results in protection from concentration exceedences above the chronic standard for reservoirs equivalent to that for discharge permitting for streams.

Aluminum loss from reservoirs by settling was found to be a function of the dissolved organic carbon (DOC) concentration in the reservoir. DOC binds aluminum chemically, thereby stabilizing it in the water column. Without stabilization by DOC, aluminum forms a hydroxide precipitate and settles out of the water column.

Simulations of aluminum dilution in the 13 reservoirs studied indicated that most of the aluminum discharges at present meet the chronic standard for aluminum, and discharge concentrations in 7 of the reservoirs could be increased and still meet the standard. Of the 4 reservoirs that do not meet the standard at the present discharge rate, 2 would not meet the standard even if no aluminum were discharged. These were reservoirs with the highest aluminum and DOC concentrations in the water column and input streams.

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Appendixes 1–4

Appendix 1. Method for solving for aluminum concentrations in reservoirs using the MatLab differential equation solver

Three MatLab files were used:

1. A file (**data_entry2.m**) to load data, which reads an Excel file of data and also requires input of the constants of equation 2, as described in the documentation after the % symbols;
2. A file (**dsol_all2.m**) that calls the differential equation, uses the loaded data to solve the equation with the solver, and plots the results; and
3. A file (**alode2.m**) that defines the differential equation.

One Excel data-input file is used with a .csv extension.

The contents of these files are given below. Documentation is provided in the comment statements that are provided after the % symbols.

Implementation involves putting all the files in the same directory and opening the MatLab software in that directory. Enter first data_entry2 at the prompt and then dsol_all2. The concentration and dilution results will be graphed and copied into a text file called “filea” in the directory that is being used.

MatLab file **data_entry2.m** [from lily pond]

```
B = importdata('Lily_DailyData_01_05_2010new.csv',' ',1);
%data for the time series inputs are loaded from the file named in single
%quotes
for k=1:2:1 %the statement that reads in the data for column 1 in the .csv file above
    B.data(:,k);
end
days=[ans]'; %data is assigned a name of days
for k=3:2:3 %reads in data from the third column
    B.data(:,k);
end
Vo=[ans]'; % data is assigned a name of Vo (for volume each day)
for k=5:2:5 %fifth column
    B.data(:,k);
end
A=[ans]'; % this is area each day in meters squared
for k=12:2:12 % 12th column
    B.data(:,k);
end
Qsr=[ans]'; % assigned Qsr (daily flow in mgd from upstream reservoir).
Qsr = Qsr.*3.785*1000000; %Qsr is converted to liters per day
for k=14:2:14 % 14 column in liters per day
    B.data(:,k);
end
Qw=[ans]';%Q Withdawal (Usage)
for k=7:2:7 %7th column in liters per day
    B.data(:,k);
end
Qsp=[ans]';% reservoir spill discharge
for k=11:2:11 % 11th column in liters per day
    B.data(:,k);
end
Qs=[ans]';%Q from streams inflowing
for k=9:2:9 % 9th column in liters per day
    B.data(:,k);
```

```

end
Qg=[ans]'; %Q of groundwater in
for k=15:2:15 %15th column in liters per day
    B.data(:,k);
end
Qe=[ans]'; %Q effluent--the volume of filter backwash water per day
Cs = 206; %concentration, in micrograms per liter, of aluminum in stream inputs
Cg = 10; %concentration, in micrograms per liter, of aluminum in groundwater inputs
Ce = 804; %concentration, in micrograms per liter, of aluminum in the filter backwash
Csr = 10; %concentration, in micrograms per liter, of aluminum in upstream reservoir
%water input
vs = 0; % settling velocity in decimeters per day
QsrCsr= Qsr.*Csr; %product of Qet aluminum fluxsr and Csr
QsCs = Qs.*Cs; %product of Qs and Cs
QgCg = Qg.*Cg; %product of Qg and Cg
QeCe = Qe.*Ce; %product of Qe and Ce
Qsv = A.*vs.*100; %product of A, vs, and 100
QCin = QgCg+QsCs+QsrCsr+QeCe; %combined terms of aluminum flux in
Qout = Qw+Qsp+Qsv; %combined terms of flow out (to be multiplied by
%concentration of aluminum in the reservoir to get aluminum flux)

```

MatLab file **dsol_all2.m** [from haggetts]

```

Vot = linspace(1,17973, 17973); %create Vot days for 1 to 17973--the
%number from October 1 1960 to December 15, 2009
QCint = linspace(1,17973, 17973); %creates same days as above for QCint
Qoutt = linspace(1,17973, 17973); %creates same days as above for Qoutt
Tspan = [1 17973]; % establishes solving period from t=1 to t=17973
IC = 15; % c(t=0) = 15 micrograms per liter
sol = ode45(@(t,c) alode2(t,c,days,QCint,QCin,Qoutt,Qout,Vot,Vo), Tspan, IC);
%sol is the solution of aluminum concentratin in the reservoir over time
%determined by the MatLab ordinary differential equation solver ode45
x = linspace(1,17973,17973); % makes again the number of that days
%1990 to 2009
y = deval(sol,x,1); %computes a value of sol (Al concentration) at each day
dil = Ce./y; %computes the dilutions for each day
l_dil = log10(dil); %computes log of the dilution factors
figure %starts a new figure
plot(x,y); %plots aluminum concentration versus day number in the figure
xlabel('TIME, IN DAYS SINCE OCTOBER 1, 1960');
ylabel('ALUMINUM, IN MICROGRAMS PER LITER');
figure %starts a new figure
plot(x,dil) %plots the dilution factor versus the day number
xlabel('TIME, IN DAYS SINCE OCTOBER 1, 1960');
ylabel('DILUTION FACTOR');
a = [x; y; dil; l_dil]'; %creates a, which contains columns of day,
%aluminum concentration, dilution factor, and log dilution factor
save filea a -ASCII; %saves a in a file called filea
x = linspace(17854,17946,17946); %creates x with values (days) between
%17854 and 17946, which is when the settling velocity sampling took place
y1 = deval(sol,x,1); %computes a value of sol (Al concentration) at each day
figure % starts figure 3
plot(x,y1); % plots aluminum concentration in a line for the period 17854 through 17946
xlabel('TIME, IN DAYS SINCE OCTOBER 1, 1960');
ylabel('ALUMINUM, IN MICROGRAMS PER LITER');
hold on %saves the last figure for the next plotting
plot(17854,24,'o',17890,22,'o',17918,21,'o',17946,26,'o'); %plots
%the aluminum concentrations for the sampling

```

MatLab file **alode2.m**

```
function dcdt = alode2(t,c,days,QCint,QCin,Qoutt,Qout,Vot,Vo)
QCin = interp1(days,QCin,t); % Interpolate the data set (days,Qw) at time t
Qout = interp1(days,Qout,t);
Vo = interp1(Vot,Vo,t);
dcdt = (-Qout.*c + QCin)/Vo;% this is the differential equation
%that is being solved
```

Sample data from Lily Pond.

day	Volume(MG)	Volume(L)	Area(Mi2)	Area(m2)	SpillVol(mgd)	SpillVol(Lpd)	Q(g)(mgd)	Q(g)(Lpd)	Q(s)(cfs)	Qin(Lpd)	SeriesResIn(mgd)	Usage(mgd)	Usage(Lpd)	Q(e)(Lpd)
1	73.47139	2.78E+08	0.079589	206136	0.295208	1117363	0	0	1.32044	3230556	0	0.406885	1540060	102195
2	73.45528	2.78E+08	0.079589	206136	0	0	0	0	0.830617	2032168	0	0.406885	1540060	102195
3	73.20601	2.77E+08	0.079576	206101	0	0	0	0	0.457888	1120257	0	0.406885	1540060	102195
4	72.92744	2.76E+08	0.079372	205571	0	0	0	0	0.410693	1004792	0	0.406885	1540060	102195
5	72.61159	2.75E+08	0.079143	204979	0	0	0	0	0.375953	919797.2	0	0.406885	1540060	102195
6	72.31863	2.74E+08	0.078884	204308	0	0	0	0	0.375797	919415.6	0	0.406885	1540060	102195
7	72.11263	2.73E+08	0.078643	203685	0	0	0	0	0.457628	1119621	0	0.406885	1540060	102195
8	71.85259	2.72E+08	0.078474	203247	0	0	0	0	0.457368	1118985	0	0.406885	1540060	102195
9	71.55886	2.71E+08	0.078261	202695	0	0	0	0	0.410523	1004375	0	0.406885	1540060	102195
10	71.2386	2.7E+08	0.07802	202070	0	0	0	0	0.3463	847248.8	0	0.406885	1540060	102195
11	70.89884	2.68E+08	0.077757	201389	0	0	0	0	0.346156	846897.3	0	0.406885	1540060	102195
12	70.59151	2.67E+08	0.077478	200667	0	0	0	0	0.346013	846546	0	0.406885	1540060	102195
13	70.27896	2.66E+08	0.077226	200014	0	0	0	0	0.345869	846194.8	0	0.406885	1540060	102195
14	69.9494	2.65E+08	0.076969	199350	0	0	0	0	0.345726	845843.8	0	0.406885	1540060	102195
15	69.61901	2.64E+08	0.076699	198649	0	0	0	0	0.372537	911438.8	0	0.406885	1540060	102195
16	69.47684	2.63E+08	0.076428	197947	0	0	0	0	0.410353	1003959	0	0.406885	1540060	102195
17	69.32189	2.62E+08	0.076311	197644	0	0	0	0	0.457108	1118350	0	0.406885	1540060	102195
18	69.09199	2.62E+08	0.076184	197315	0	0	0	0	0.456849	1117716	0	0.406885	1540060	102195
19	68.93124	2.61E+08	0.075995	196826	0	0	0	0	0.569427	1393147	0	0.406885	1540060	102195
20	72.64468	2.75E+08	0.075863	196485	0	0	0	0	3.983369	9745614	0	0.406885	1540060	102195
21	73.47139	2.78E+08	0.078911	204378	2.854871	10805687	0	0	6.536171	15991235	0	0.406885	1540060	102195
22	73.47139	2.78E+08	0.079589	206136	2.099165	7945341	0	0	4.142661	10135334	0	0.406885	1540060	102195
23	73.47139	2.78E+08	0.079589	206136	1.131916	4284302	0	0	2.604379	6371810	0	0.406885	1540060	102195
24	73.47139	2.78E+08	0.079589	206136	2.14382	8114360	0	0	3.301716	8077898	0	0.406885	1540060	102195
25	73.47139	2.78E+08	0.079589	206136	3.636054	13762464	0	0	4.434658	10849726	0	0.406885	1540060	102195
26	73.47139	2.78E+08	0.079589	206136	1.577989	5972687	0	0	3.301127	8076455	0	0.406885	1540060	102195

(Continues through day 17973)

Appendix 2. Massachusetts water-supply reservoirs not included in the application of dilution factors.

[WFP, water-filtration plant; WTP, water-treatment plant; Permit number, the National Pollutant Discharge Elimination System (NPDES) permit number]

Facility	Permit number	Receiving water	Latitude (decimal degree)	Longitude (decimal degree)	Reason for disqualification from dilution-factor investigation
Fitchburg Regional WFP	MAG640039	Wyman Pond	42.533	-71.884	Not sampled: Discharge is to a stream leading to Wyman Pond, not to Wyman Pond directly.
Littleton Spectacle Pond WTP	MAG640002	Spectacle Pond	42.564	-71.516	Not sampled: No use of aluminum in treatment process.
Peabody Coolidge Avenue WTP	MAG64006	Lower Spring Pond	42.506	-70.945	Not sampled: Plant under construction, no access or data given.
Peabody Winona Pond	MAG640028	Winona Pond	42.535	-71.009	Not sampled: Plant under construction, no access or data given.
Randolph WTP	MAG640032	Great Pond	42.198	-71.047	Unknown discharge from Braintree and not enough Randolph discharge information to model.
Rockport WTP	MAG640021	Cape Pond	42.640	-70.629	Not sampled: Discharge is to a wetland so that the reservoir simulations would not apply.
Rutland WTP	MAG640033	Muschopauge Pond	42.383	-71.921	Not sampled: Effluent is discharged to an infiltration basin rather than to the reservoir.
Westborough WTP	MAG640007	Hocomonco Pond	42.272	-71.650	Not sampled: No use of aluminum in treatment process.

Appendix 3. Bathymetry- and flow-data sources for 13 Massachusetts drinking-water supply reservoirs.

[Data were collected August–November 2009; WTP, water-treatment plant; Mgal/d, million gallons per day; DMR, discharge monitoring report; MassDEP, Massachusetts Department of Environmental Protection; USGS, U.S. Geological Survey; SYE, Massachusetts Sustainable Yield Estimator; WTF, water-treatment facility; %, percent; ~, approximately]

Facility	Inflows data source/quality notes	Effluent flow data source	Bathymetry source
Andover WTP	Haggetts Pond—Receives inflow from Merrimack River diversion and Fish Brook Reservoir. These inflow volumes were obtained from the supplier for the years 2004–2009. Daily data reflect reservoir levels when withdrawals were at the system firm yield of 4.582 Mgal/d until January 2004; after this date, actual monthly diversion and withdrawal were used, until December 2009. Withdrawals after 2004 represent finished flow totals.	Based on supplier-provided monthly summary difference for withdrawal and delivery for 2004–2009.	Bathymetry provided by supplier.
Ashburnham/Winchendon WTP	Naukeag Lake—This is a stand-alone reservoir with no water imports from other reservoirs or diversions; there are no groundwater interactions for this reservoir. No information was available regarding the usable capacity for this lake or the intake elevation, so a firm yield could not be determined. Peak-usage factors and one month of daily data from September 2009 were available. The average September finished-withdrawals volume along with the peak-usage factors were used to get average monthly finished withdrawals (considerably lower than actual withdrawals for this lake), and these were used for the entire simulation.	Based on DMR sheets to MassDEP.	Bathymetry collected by USGS.
Cambridge WTP	Fresh Pond—Gets water from Stony Brook Reservoir. Several years of daily flow data were available from Stony Brook into Fresh Pond. Simulation was done with withdrawals at the estimated firm yield of 10.879 Mgal/d until January 1, 1991, when actual monthly usage was available from the supplier. Monthly averages were disaggregated into constant daily flow values.	From supplier-provided representative (October 2009) backwash average.	Bathymetry provided by supplier.
Clinton WTP	Discharge to unnamed pond—This pond has no withdrawals from it, so the program was run with zero usage. Methodology may not be good for this pond. Anecdotally, this is primarily a groundwater-fed pond with very little inflowing surface water. The firm yield uses a very simplistic groundwater calculation based on change in storage, but since there are no withdrawals, there will be very little change in storage, and therefore, very little groundwater inflow. A full transient groundwater model may be needed for better estimates for this pond.	From supplier-supplied pumping rates January 2006 through September 2009.	Bathymetry collected by USGS.
Cohasset Lily Pond WTP	Lily Pond—This reservoir receives water imported from Aaron River Reservoir, but no data on the volume of water that is imported was available. SYE database is incomplete for this reservoir as well, so the simulation was run as a stand-alone reservoir without any imports. Simulation was done using withdrawals equal to the firm yield of 0.432 Mgal/d. Winter and summer estimates of water supplier were less than state value, so used state value.	Average from MassDEP DMRs. (Average for January 2009 from supplier: 0.01).	Bathymetry collected by USGS.
Gardner Crystal Lake WTP	Crystal Lake—Receives water pumped from Perley Brook Reservoir. No pumping volumes were available from supplier for Perley Brook. Annual average pumping volumes from SYE wateruse database were used and disaggregated using peak-usage factors for Crystal Lake. Model was run with annual withdrawals set at the firm yield of 1.042 Mgal/d until January 1, 2005. Daily withdrawals from supplier for January 1, 2005–August 31, 2008 were used, and after August 2008, average daily flow values from the supplier were used.	Daily difference for supplier provided withdrawal and delivery from 2005 to August 2009, then repeated for 2008 through December 15, 2009. Before 2005, used average of record.	Bathymetry provided by supplier.
Manchester-by-the-Sea WTP	Gravelly Pond—No diversions or water imports. Daily data reflect reservoir levels when withdrawals were at the reservoir firm yield of 0.201 Mgal/d.	Effluent volumes came from monthly data for 11 months in 2009 from the supplier.	Bathymetry collected by USGS.
New Bedford Quittacas WTP	Little Quittacas—Spillway elevation estimated from topographic maps. This reservoir receives water from Great Quittacas Pond, but no pumping volumes were available for this, so it was run as a stand-alone reservoir, without any water imports. Withdrawals were set at the firm yield of 1.421 Mgal/d.	Daily values for effluent volume for 2005–2006 from the supplier.	Bathymetry provided by supplier.

Appendix 3. Bathymetry- and flow-data sources for 13 Massachusetts drinking-water supply reservoirs.—Continued

[Data were collected August–November 2009; WTP, water-treatment plant; Mgal/d, million gallons per day; DMR, discharge monitoring report; MassDEP, Massachusetts Department of Environmental Protection; USGS, U.S. Geological Survey; SYE, Massachusetts Sustainable Yield Estimator; WTF, water-treatment facility; %, percent; ~, approximately]

Facility	Inflows data source/quality notes	Effluent flow data source	Bathymetry source
Northampton WTP	Mountain Street Reservoir—Does not receive any water from other reservoirs or diversions. No value of transmissivity was available for this reservoir, but because only a small portion of the reservoir is in contact with sand and gravel, the model was not very sensitive to this parameter for this reservoir. Simulations for this reservoir were run twice, once with a very low transmissivity and once with a relatively high transmissivity. Reservoir volumes and groundwater volumes were nearly identical for both runs. The final simulation was done with a medium transmissivity of 1,350 ft ² /day and withdrawals at the firm yield level of 0.588 Mgal/d.	Daily values for effluent volume for 2008 from the supplier.	Bathymetry provided by supplier.
Salem and Beverly Water Supply Board	Wenham—Receives water diversions from Longham Reservoir, Putnamville Reservoir, and the Ipswich River. Monthly data for these diversion volumes from 2004 to 2008 from supplier and from 1989–1995 from an Ipswich River basin model (Zarriello and Ries, 2000) were averaged for each month. This reservoir is in contact with sand and gravel, but no transmissivity values were available in the hydrologic atlases. MassGIS has a GIS layer of medium- and high-yield aquifers, which intersect part of Wenham Lake. For the rest of the lake, a low-transmissivity area was assumed (less than 1,350), and a rough weighted average was taken. A second run with high transmissivity of 4,000 was completed, which increased the groundwater fluxes by about 50%, but groundwater fluxes are very small compared to other fluxes in the system, so groundwater is not very substantial. Withdrawals were set at 7.992 Mgal/d, which is the firm yield calculated by this model. Note that this is considerably lower than the firm yield calculated by an Ipswich River basin model (Zarriello and Ries, 2000) and also much lower than current water usage (~14 Mgal/d). If the model is run using current usage, it goes dry in the 1960s drought and never recovers. There are multiple reasons why these simulations will be inaccurate for reservoirs like this. The diversions in this system operate under some complex rules which we are not simulating with the firm yield. This will be the case for other reservoir systems such as Holden and Quittacas as well.	One year 2008–2009 of daily flow data from the supplier.	Bathymetry collected by USGS.
Weymouth Great Pond WTP	Great Pond (Weymouth)—This pond receives water pumped from South Cove Reservoir, which we are not modeling. The town has 10 years of monthly pumping volumes from South Cove (figure 5 in their firm yield report), but they didn't give us the numbers. Annual pumping volumes from 2000 to 2004 from the SYE water-use database were used and disaggregated using the peak-usage factors for Weymouth Pond and then further disaggregated from monthly volumes into daily. Reservoir simulation was done with withdrawals set at the system firm-yield level of 3.061 Mgal/d.	One year 2008–2009 of daily flow data from the supplier.	Collected for previous firm-yield study (Waldron and Archfield, 2006).
Winchester WTP	South Reservoir—Run in series with North and Middle Reservoirs. South Reservoir is the terminal reservoir. Water from North Reservoir is pumped into Middle Reservoir and then flows by gravity into South Reservoir. The firm yield from each upstream river was used instead of taking the system firm yield entirely from South Reservoir (this is the way the Firm-Yield Estimator tool runs reservoirs in series; this may not be correct for this system).	One year of monthly average discharges from the supplier.	Collected for previous firm-yield study (Waldron and Archfield, 2006).
Worcester WTP	Holden—This reservoir gets a small amount of backwash water from the treatment plant and also releases some water back into Holden #1. It can also get water gravity fed from Holden #1, but there's no volume data for this. Apparently, Worcester Department of Public Works mostly try to keep this reservoir at full pool. Withdrawals are taken out of Holden #1, not Holden #2, so the Firm-Yield Estimator tool was run with 0 water withdrawals from Holden Reservoir #2.	One value of effluent discharge (1 Mgal/d) from a diagram from the supplier.	Bathymetry collected by USGS.

Appendix 4. Water-quality data from 13 Massachusetts reservoirs, influent streams, filter-backwash effluents containing aluminum, and streams sampled during August–November 2009.

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; µg/L, micrograms per liter; WTP, water-treatment plant; WTF, water-treatment facility; <, less than; --, no data]

Station name	Station number	Latitude (decimal degrees)	Longitude (decimal degrees)	Date	Time	Dissolved oxygen (mg/L)	pH, water, unfiltered field (stan- dard units)	Specific conductance, water, unfiltered (µS/cm at 25 degrees Celsius)	Temperature, water (degrees Celsius)	Sampling depth (meters)	Aluminum, water, unfiltered recoverable (µg/L)	Organic carbon, water, unfiltered filtered (mg/L)
Andover WTP												
Andover WTF Backwash Effluent	423841071114801	42.645	-71.197	20090818	1330	--	--	--	--	--	2,190	--
Andover WTF Backwash Effluent	423841071114801	42.645	-71.197	20090923	1330	10.7	6.9	388	--	--	4,040	--
Andover WTF Backwash Effluent	423841071114801	42.645	-71.197	20091006	1200	7.9	6.7	380	--	--	4,780	--
Andover WTF Backwash Effluent	423841071114801	42.645	-71.197	20091116	1200	7.9	6.5	370	--	--	4,220	--
Haggetts Pond Deep Hole	423844071115501	42.646	-71.199	20090818	1200	8.4	7.8	372	--	--	24	4.7
Haggetts Pond Deep Hole	423844071115501	42.646	-71.199	20090923	1320	9.6	6.9	353	--	--	22	4.5
Haggetts Pond Deep Hole	423844071115501	42.646	-71.199	20091021	1400	9.8	6.8	347	--	--	21	4.4
Haggetts Pond Deep Hole	423844071115501	42.646	-71.199	20091118	1330	9.9	7	339	--	--	26	4.3
Unnamed Tributary at Haggetts Pond	423905071121301	42.651	-71.204	20090818	1100	1.3	6.3	321	--	--	41	8.7
Unnamed Tributary at Haggetts Pond	423905071121301	42.651	-71.204	20090923	1300	1.1	6.1	409	--	--	30	6
Unnamed Tributary at Haggetts Pond	423905071121301	42.651	-71.204	20091021	1350	5.3	6.6	471	--	--	21	4.8
Unnamed Tributary at Haggetts Pond	423905071121301	42.651	-71.204	20091118	1230	5.2	6.6	336	--	--	77	7.1
Ashburnham/Winchendon WTP												
Upper Naukeag Lake Deep Hole	423919071552401	42.655	-71.923	20090826	1510	7.8	6.5	49	--	--	37	2.6
Upper Naukeag Lake Deep Hole	423919071552401	42.655	-71.923	20090922	1210	8.7	6.8	49	--	--	21	2.3
Upper Naukeag Lake Deep Hole	423919071552401	42.655	-71.923	20091020	1250	11	7	49	--	--	21	2.2
Upper Naukeag Lake Deep Hole	423919071552401	42.655	-71.923	20091110	1300	11.1	6.1	48	--	--	23	2.2
Upper Naukeag Lake Treatment Facility Back- wash Effluent	423943071560601	42.662	-71.935	20090826	1400	7.1	6.9	71	--	--	264	--
Upper Naukeag Lake Treatment Facility Back- wash Effluent	423943071560601	42.662	-71.935	20090922	1240	8.8	7.3	68	--	--	3,390	--
Upper Naukeag Lake Treatment Facility Back- wash Effluent	423943071560601	42.662	-71.935	20091020	1230	10.4	7.7	62	--	--	183	--
Cambridge WTP												
Stony Brook Diversion Outlet	422248071085701	42.380	-71.149	20090819	1130	6.7	7.2	520	--	--	24	5
Stony Brook Diversion Outlet	422248071085701	42.380	-71.149	20090923	1030	8.3	7.2	621	--	--	8	4.1
Stony Brook Diversion Outlet	422248071085701	42.380	-71.149	20091021	1120	10.4	7.4	611	--	--	9	3.8
Stony Brook Diversion Outlet	422248071085701	42.380	-71.149	20091118	1030	9.4	7.7	458	--	--	26	5.3

Appendix 4. Water-quality data from 13 Massachusetts reservoirs, influent streams, filter-backwash effluents containing aluminum, and streams sampled during August–November 2009.—Continued

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; µg/L, micrograms per liter; WTP, water-treatment plant; WTF, water-treatment facility; <, less than; --, no data]

Station name	Station number	Latitude (decimal degrees)	Longitude (decimal degrees)	Date	Time	Dissolved oxygen (mg/L)	pH, water, unfiltered field (standard units)	Specific conductance, water, unfiltered (µS/cm at 25 degrees Celsius)	Temperature, water (degrees Celsius)	Sampling depth (meters)	Aluminum, water, unfiltered recoverable (µg/L)	Organic carbon, water, filtered (mg/L)
Cambridge WTP—Continued												
Cambridge WTP Backwash Effluent	422301071084101	42.384	-71.145	20090819	1240	--	--	--	--	--	1,080	--
Cambridge WTP Backwash Effluent	422301071084101	42.384	-71.145	20090929	0830	--	6.8	550	--	--	1,260	--
Cambridge WTP Backwash Effluent	422301071084101	42.384	-71.145	20091019	0850	10.2	7.5	574	--	--	2,440	--
Cambridge WTP Backwash Effluent	422301071084101	42.384	-71.145	20091118	1100	10.4	7	564	--	--	1,030	--
Fresh Pond Site Brook at Cambridge, Mass.	422300071091001	42.383	-71.152	20090819	1200	6.6	7.2	519	--	--	17	--
Fresh Pond Site F4 at Cambridge, Mass.	422310071085901	42.386	-71.149	20090819	1215	7	7.2	518	--	--	17	--
Fresh Pond, Deep Hole at Cambridge, Mass.	422305071090001	42.385	-71.149	20090819	1100	7.1	7.2	510	--	--	17	4.1
Fresh Pond, Deep Hole at Cambridge, Mass.	422305071090001	42.385	-71.149	20090923	1020	9.3	7.3	535	--	--	11	3.5
Fresh Pond, Deep Hole at Cambridge, Mass.	422305071090001	42.385	-71.149	20091021	1030	9.7	7.6	556	--	--	19	3.5
Fresh Pond, Deep Hole at Cambridge, Mass.	422305071090001	42.385	-71.149	20091118	1020	9.8	7.6	548	--	--	21	3.3
Clinton WTP												
Clinton WTP Backwash Effluent	422438071420401	42.411	-71.701	20090909	1520	7.7	7.8	166	--	--	3,610	--
Upper Pond Tributary	422442071420001	42.412	-71.700	20090909	1400	8.4	6.7	184	--	--	13	1.2
Small Pond Deep Hole	422443071420301	42.412	-71.701	20090909	1430	7.2	6.7	170	--	--	221	1.8
Cohasset WTP												
Aaron River above Lily Pond	421257070490201	42.216	-70.817	20090924	1140	6.5	6.1	117	--	--	204	15.2
Aaron River above Lily Pond	421257070490201	42.216	-70.817	20091022	1150	8.4	6.2	117	--	--	202	15.1
Aaron River above Lily Pond	421257070490201	42.216	-70.817	20091119	1300	8.6	6.8	115	--	--	214	14.4
Lily Pond Deep Hole	421326070485801	42.224	-70.816	20090924	1130	9.5	7.5	128	--	--	284	15.5
Lily Pond Deep Hole	421326070485801	42.224	-70.816	20091022	1140	10.1	6.5	121	--	--	357	15.1
Lily Pond Deep Hole	421326070485801	42.224	-70.816	20091119	1230	9.0	6.4	119	--	--	414	14.4
Cohasset WTP Backwash Effluent	421334070490601	42.226	-70.818	20090924	1100	5.8	7.1	323	--	--	827	--
Cohasset WTP Backwash Effluent	421334070490601	42.226	-70.818	20091022	1110	9.9	7.9	283	--	--	781	--
Cohasset WTP Backwash Effluent	421334070490601	42.226	-70.818	20091119	1200	10.7	7.8	258	--	--	380	--

Appendix 4. Water-quality data from 13 Massachusetts reservoirs, influent streams, filter-backwash effluents containing aluminum, and streams sampled during August–November 2009. —Continued

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; µg/L, micrograms per liter; WTP, water-treatment plant; WTF, water-treatment facility; <, less than; --, no data]

Station name	Station number	Latitude (decimal degrees)	Longitude (decimal degrees)	Date	Time	Dissolved oxygen (mg/L)	pH, water, unfiltered field (standard units)	Specific conductance, water, unfiltered (µS/cm at 25 degrees Celsius)	Temperature, water (degrees Celsius)	Sampling depth (meters)	Aluminum, water, unfiltered recoverable (µg/L)	Organic carbon, water, filtered (mg/L)
Gardner WTF												
Crystal Lake WTF Backwash Effluent	423459071592101	42.583	-71.989	20090820	1415	7.3	7.2	252	--	--	1,970	--
Crystal Lake WTF Backwash Effluent	423459071592101	42.583	-71.989	20090922	1100	8.7	7.3	253	--	--	1,670	--
Crystal Lake WTF Backwash Effluent	423459071592101	42.583	-71.989	20091020	1100	10	8	248	--	--	2,290	--
Crystal Lake WTF Backwash Effluent	423459071592101	42.583	-71.989	20091110	1030	11.4	7.8	242	--	--	1,650	--
Crystal Lake Deep Hole	423501071593501	42.584	-71.993	20090820	1300	6.5	7.3	249	27.3	0	21	3
Crystal Lake Deep Hole	423501071593501	42.584	-71.993	20090820	1320	6.8	7.3	249	27.3	1	17	--
Crystal Lake Deep Hole	423501071593501	42.584	-71.993	20090820	1325	6.4	7.2	248	26.4	2	18	--
Crystal Lake Deep Hole	423501071593501	42.584	-71.993	20090820	1330	6.8	7.1	247	25.1	3	13	--
Crystal Lake Deep Hole	423501071593501	42.584	-71.993	20090820	1335	5.8	7	248	24.1	4	12	--
Crystal Lake Deep Hole	423501071593501	42.584	-71.993	20090820	1340	5	6.8	248	23.3	5	10	--
Crystal Lake Deep Hole	423501071593501	42.584	-71.993	20090820	1345	4.8	6.7	248	22.1	6	10	--
Crystal Lake Deep Hole	423501071593501	42.584	-71.993	20090820	1350	4.8	6.5	254	18.2	7	8	--
Crystal Lake Deep Hole	423501071593501	42.584	-71.993	20090820	1355	3.6	6.4	259	14.2	8	9	--
Crystal Lake Deep Hole	423501071593501	42.584	-71.993	20090820	1400	2	6.3	261	11.5	9	10	--
Crystal Lake Deep Hole	423501071593501	42.584	-71.993	20090820	1405	0.2	6.4	269	10	10	10	--
Crystal Lake Deep Hole	423501071593501	42.584	-71.993	20090922	1010	8.5	7.2	244	--	--	10	2.7
Crystal Lake Deep Hole	423501071593501	42.584	-71.993	20091020	1020	9.8	6.9	243	--	--	12	2.8
Crystal Lake Deep Hole	423501071593501	42.584	-71.993	20091110	1000	11	7.5	238	--	--	12	2.7
Perley Brook Diversion Outlet	423525071594401	42.590	-71.996	20090820	1220	2.5	5.8	174	--	--	132	6.7
Perley Brook Diversion Outlet	423525071594401	42.590	-71.996	20090922	950	7.5	6.6	179	--	--	81	5.9
Perley Brook Diversion Outlet	423525071594401	42.590	-71.996	20091020	1000	9.5	6.5	194	--	--	85	5.4
Perley Brook Diversion Outlet	423525071594401	42.590	-71.996	20091110	930	9.8	7.6	190	--	--	91	6
Tributary 1 Mouth	423527071592301	42.591	-71.990	20090820	1140	7.5	7.1	502	--	--	43	8.1
Tributary 1 Mouth	423527071592301	42.591	-71.990	20090922	930	9.7	7.5	488	--	--	18	5.7
Tributary 1 Mouth	423527071592301	42.591	-71.990	20091020	950	12.4	7.7	439	--	--	52	5.2
Tributary 1 Mouth	423527071592301	42.591	-71.990	20091110	900	11.4	7.5	405	--	--	92	6.5

Appendix 4. Water-quality data from 13 Massachusetts reservoirs, influent streams, filter-backwash effluents containing aluminum, and streams sampled during August–November 2009.—Continued

[mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; µg/L, micrograms per liter; WTP, water-treatment plant; WTE, water-treatment facility; <, less than; --, no data]

Station name	Station number	Latitude (decimal degrees)	Longitude (decimal degrees)	Date	Time	Dissolved oxygen (mg/L)	pH, water, unfiltered field (standard units)	Specific conductance, water, unfiltered (µS/cm at 25 degrees Celsius)	Temperature, water (degrees Celsius)	Sampling depth (meters)	Aluminum, water, unfiltered recoverable (µg/L)	Organic carbon, water, filtered (mg/L)
Manchester by the Sea WTP												
Manchester WTP Effluent	423548070482201	42.597	-70.806	20090915	1210	7.5	7.2	177	--	--	107	--
Gravelly Pond Site 1	423552070483501	42.598	-70.810	20090915	1310	8	7.3	159	--	--	<6	2.9
Gravelly Pond Deep Hole	423555070483701	42.599	-70.810	20090915	1400	7.8	7.6	160	--	--	<6	3
Gravelly Pond Site 2	423601070484001	42.600	-70.811	20090915	1320	7.7	7.4	160	--	--	<6	3.1
Fish Brook above Fish Brook Pumping Station	424113071132301	42.687	-71.223	20090819	900	--	--	175	--	--	23	10
Fish Brook above Fish Brook Pumping Station	424113071132301	42.687	-71.223	20090916	1200	--	7.7	400	--	--	71	6.1
Fish Brook above Fish Brook Pumping Station	424113071132301	42.687	-71.223	20091014	1200	7	6.8	276	--	--	44	5
Fish Brook above Fish Brook Pumping Station	424113071132301	42.687	-71.223	20091111	1200	6.6	7	513	--	--	221	8.7
Merrimack River at Fish Brook Pumping Station	424113071132601	42.687	-71.224	20090819	910	--	--	275	--	--	121	4.1
New Bedford WTP												
New Bedford Quittacas WTP Effluent	414703070545401	41.784	-70.915	20090916	1200	8.4	6.1	107	--	--	438	--
Unnamed Diversion Tributary at Mouth	414711070550601	41.786	-70.918	20090916	1400	1.3	5.1	109	--	--	287	23
Little Quittacas Reservoir Raw Water at Tap	414714070545201	41.787	-70.914	20090916	1430	6.5	7	86	--	--	39	6.7
Great Quittacas Tributary	414731070542501	41.792	-70.907	20090916	1240	7.9	6.8	86	--	--	47	7.1
Little Quittacas Reservoir Site 1	414734070551401	41.793	-70.921	20090916	1340	8.3	7.1	84	--	--	35	6.9
Spring Brook Tributary above Culvert	414808070552401	41.802	-70.923	20090916	1310	9.5	6.3	137	--	--	107	5.6
Northampton WTP												
Mountain Street Reservoir Deep Hole	422404072401501	42.401	-72.671	20090910	1200	7	7.2	75	--	--	<5	1.7
Northampton WTP Effluent	422421072401801	42.406	-72.672	20090910	1140	8.2	6.8	57	--	--	233	--
Unnamed Tributary 1 at Mouth	422441072400501	42.411	-72.668	20090910	1300	9.3	7.7	89	--	--	190	0.9
Randolph WTP												
Great Pond Deep Hole	421154071025001	42.198	-71.047	20091006	1510	10.6	7.5	346	--	--	63	3.8
Salem/Beverly Supply Board												
Salem/Beverly WTP Backwash Effluent	423458070532901	42.583	-70.891	20091027	1030	10.1	7.7	379	--	--	672	--
Wenham Lake Deep Hole	423523070532801	42.590	-70.891	20091027	1330	8.5	7.4	328	--	--	12	4.6
Unnamed Tributary 2	423534070540501	42.593	-70.901	20091027	1130	7.2	7.4	392	--	--	31	8.3
North Diversion Inflow	423601070535001	42.600	-70.897	20091027	1100	10	7.5	265	--	--	12	5.7

Appendix 4. Water-quality data from 13 Massachusetts reservoirs, influent streams, filter-backwash effluents containing aluminum, and streams sampled during August–November 2009.—Continued

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Station name	Station number	Latitude (decimal degrees)	Longitude (decimal degrees)	Date	Time	Dissolved oxygen (mg/L)	pH, water, unfiltered field (standard units)	Specific conductance, water, unfiltered (µS/cm at 25 degrees Celsius)	Temperature, water (degrees Celsius)	Sampling depth (meters)	Aluminum, water, unfiltered recoverable (µg/L)	Organic carbon, water, filtered (mg/L)
Weymouth WTP												
Unnamed Tributary 1 at Mouth	420910070575602	42.153	-70.965	20091022	1440	1.6	4.6	115	--	--	286	25.9
Weymouth Great Pond Deep Hole	420920070581501	42.156	-70.971	20091022	1400	10.7	7.3	124	--	--	102	7.8
Weymouth Drinking WTP Effluent	420959070580401	42.166	-70.968	20091022	1310	8	7.2	150	--	--	442	--
Winchester WTP												
Winchester WTP Effluent	422627071071401	42.441	-71.121	20090917	1000	9.6	7.3	141	--	--	1,320	--
Winchester South Reservoir Deep Hole	422639071065601	42.444	-71.116	20090917	1210	7.6	7.2	135	20.5	0	12	2.3
Winchester South Reservoir Deep Hole	422639071065601	42.444	-71.116	20090917	1215	7.7	7	135	20.5	1	10	--
Winchester South Reservoir Deep Hole	422639071065601	42.444	-71.116	20090917	1220	7.6	7	135	20.5	2	10	--
Winchester South Reservoir Deep Hole	422639071065601	42.444	-71.116	20090917	1225	7.5	7	135	20.5	3	10	--
Winchester South Reservoir Deep Hole	422639071065601	42.444	-71.116	20090917	1230	7.3	7	135	20.5	4	10	--
Winchester South Reservoir Deep Hole	422639071065601	42.444	-71.116	20090917	1235	7.4	7	135	20.4	5	11	--
Winchester South Reservoir Deep Hole	422639071065601	42.444	-71.116	20090917	1240	7.3	7.1	134	20.4	6	11	--
Winchester South Reservoir Deep Hole	422639071065601	42.444	-71.116	20090917	1245	5.2	6.5	116	18.2	7	14	--
Winchester South Reservoir Deep Hole	422639071065601	42.444	-71.116	20090917	1250	3.4	6.3	112	13.7	8	10	--
Winchester South Reservoir Deep Hole	422639071065601	42.444	-71.116	20090917	1255	1.9	6.3	114	11.5	9	9	--
Winchester South Reservoir Deep Hole	422639071065601	42.444	-71.116	20090917	1300	0.4	6.4	118	10.2	10	6	--
Winchester South Reservoir Deep Hole	422639071065601	42.444	-71.116	20090917	1305	0.3	6.6	146	9.4	11	<6	--
Winchester Middle Reservoir Outlet	422702071065701	42.451	-71.116	20090917	1140	9.1	7.5	255	--	--	10	2.7
Worcester WTP												
Holden 2 Reservoir Deep Hole	421748071520001	42.297	-71.867	20090902	1200	7.4	7.3	100	--	--	32	1.5
Unnamed Tributary 1 at Holden Reservoir 2	421753071520701	42.298	-71.869	20090902	1140	9.9	7.7	114	--	--	21	1
Holden 2 WTP Backwash Effluent	421808071520601	42.302	-71.868	20090827	1200	--	6.9	132	--	--	748	--

Prepared by the Pembroke Publishing Service Center.

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