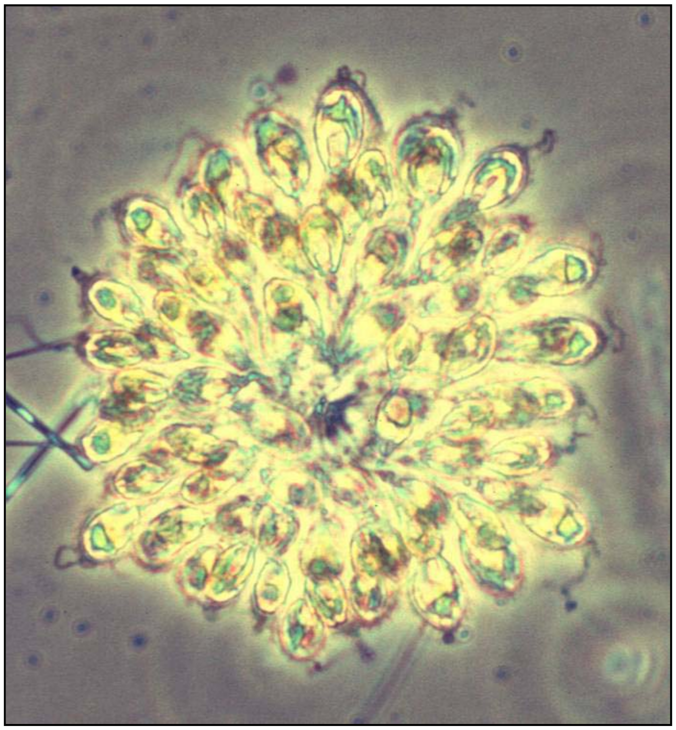
Nutrient and Plankton Dynamics in Wachusett Reservoir: Results of the DCR/DWSP's 1998-2002 Monitoring Program, a Review of Plankton Data from Cosgrove Intake, and an Evaluation of Historical Records



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Division of Water Supply Protection
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Cover Photograph:

A colonial chrysophyte of the genus *Synura*, this organism is one of several phytoplankton taxa that can cause unpleasant taste and odors in water supplied to consumers. The colony is about 120 microns in diameter. Photographs of other phytoplankton organisms observed in Wachusett Reservoir are provided in Appendix E.

Acknowledgements:

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Laboratory analysis of water samples was performed at the Massachusetts Water Resources Authority (MWRA) Central Laboratory on Deer Island with guidance and support from Diane Rossi, Lisa Wong, and Edward Caruso of the MWRA Client Services Department. Microscopic analysis of plankton samples collected from 1987 through 2002, mainly at Cosgrove Intake, was performed by Larry Pistrang. Analysis of plankton and photomicrography of specimens collected in the 1998-99 reservoir-wide sampling program and in subsequent sampling was performed by David Worden.

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Abstract:

This report details the scope, methods, and results of an intensive program of monthly sampling and analysis of nutrients and plankton in Wachusett Reservoir conducted from October 1998 through September 1999 and continued, with some modifications, on a quarterly schedule to the present day. Laboratory measurement of nutrient concentrations was performed by Massachusetts Water Resources Authority (MWRA) staff of the Deer Island Central Laboratory at a higher level of precision and sensitivity than any previous study. The spatial coverage of the program (four stations each sampled at various depths) and frequency of sampling, combined with the efficacy of laboratory measurements provides the most comprehensive database currently available on nutrient and plankton dynamics in Wachusett Reservoir.

Also presented in this report is a review of plankton data generated independently from the following sources: (1) DWSP sampling conducted weekly (ice conditions permitting) at Cosgrove Intake since 1987; (2) historical reservoir sampling conducted in 1988, 1989, 1995, and 1996; and (3) historical data compiled by the MWRA. Additionally, a detailed characterization of the Quabbin "interflow," a hydrodynamic phenomenon resulting from the annual transfer of water from Quabbin Reservoir to Wachusett via the Quabbin Aqueduct is presented. Finally, this report integrates historical nutrient and plankton records and related information generated from numerous consultant studies of Wachusett Reservoir.

Major findings include the following: (1) marked seasonal and vertical variations in nutrient concentrations mediated by phytoplankton dynamics; (2) interannual shifts in nutrient concentrations and the intensities of other parameters corresponding to the divergent influences of the Quabbin transfer and the Wachusett watershed; (3) a phytoplankton community dominated by diatoms and chrysophytes typical of many oligotrophic, softwater systems located in the temperate zone; and (4) an annual cycle of phytoplankton succession and abundance also characteristic of this type of system, but with additional features unique to Wachusett Reservoir.

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1.0 INTRODUCTION

Wachusett Reservoir is an impoundment of the Nashua River completed in 1908 as a public water supply for Boston. It measures 15.8 square kilometers (6.1 square miles) in surface area with a capacity of 250 million cubic meters (66 billion gallons) of water. Today, in conjunction with Quabbin Reservoir located approximately 25 miles to the west, Wachusett Reservoir provides water to 2.2 million residents of Greater Boston.

Beginning in October of 1998, DWSP staff initiated a year-long program of monthly sampling of Wachusett Reservoir at multiple stations and depths. The goal of this program was to document current nutrient and plankton dynamics and to update the existing database on nutrient concentrations and plankton characteristics. At the conclusion of monthly sampling in September 1999 a modified program of nutrient monitoring was continued on a quarterly schedule.

This report details the scope and methods of both the monthly and quarterly components of the monitoring program and presents an analysis of the results through December 2002. Also presented in this report is a review of plankton data generated independently from the following sources: (1) DWSP sampling conducted weekly (ice conditions permitting) at Cosgrove Intake since 1987; (2) historical reservoir sampling conducted in 1988, 1989, 1995, and 1996; and (3) historical data compiled by the Massachusetts Water Resources Authority (MWRA). Additionally, a detailed characterization of the Quabbin "interflow," a hydrodynamic phenomenon resulting from the annual transfer of water from Quabbin Reservoir to Wachusett via the Quabbin Aqueduct is presented. Finally, this report integrates historical nutrient and plankton records and related information generated from numerous consultant studies of Wachusett Reservoir.

2.0 FIELD PROCEDURES AND LABORATORY METHODS

Samples for analysis of nutrients and plankton were collected concurrently during the 1998-99 year of monthly sampling. Plankton sampling at Cosgrove Intake was initiated in 1987 and has been conducted routinely since that time independent of other sampling programs. Field procedures and laboratory methods for nutrients and plankton are described separately in the sections that follow.

2.1 Nutrients

Sampling and analysis of water samples was undertaken in collaboration with Massachusetts Water Resources Authority (MWRA) staff at the Deer Island Central Laboratory who provided sample containers and where all grab samples were sent for analysis. Sampling protocol, chain-of-custody documentation, and sample delivery was performed in accordance with MWRA guidance. A list of the parameters measured and details of methodology, sample preservation, holding times, and detection limits are summarized in Table 1 below.

Grab samples were collected monthly at three locations in the main basin of the reservoir (Cosgrove Intake/Station 3409, Basin North/Station 3417, and Basin South/Station 3412) and at a fourth location in Thomas Basin weather and ice conditions permitting (see Figure 1). Samples were collected in the epilimnion, metalimnion, and hypolimnion during the period of thermal stratification (generally May through early November) and near the top and bottom of the water column during periods of isothermy and mixing. Water column profiles of temperature, dissolved oxygen, and other parameters measured with a multiprobe were evaluated in the field to determine depths for metalimnetic samples.

Table 1 - Wachusett Reservoir Nutrient Analyses: Laboratory Methods

Parameter and Method (EPA, 1983)	Preservation	Holding Time	Detection Limit
Total Phosphorus EPA - 365.4	Sulfuric Acid	28 days	5 ug/L
Ammonia-Nitrogen EPA - 350	Filtered and Frozen	Indefinite	5 ug/L
Nitrate-Nitrogen EPA - 353.2	Filtered and Frozen	Indefinite	5 ug/L
Total Kjeldahl-Nitrogen EPA - 351.2	Sulfuric Acid	28 days	600 ug/L
Silica EPA - 200.7	Nitric Acid	28 days	10 ug/L
Alkalinity EPA - 310.1	Refrigeration	14 days	10 ug/L as $CaCO_3$

A Van Dorn Bottle was used to collect grab samples at depth, whereas surficial grabs were collected by hand. In order to reduce interference in the lab analysis for ammonia and nitrate, samples to be analyzed for these parameters were filtered in the field using a glass fiber Acrodisc (pore size = 1 micron; Gelman Sciences, Inc.) attached to a syringe. Samples were preserved with acid or filtered in the field as indicated in the above table and stored in a cooler until they were transferred to a refrigerator in the DWSP laboratory. Samples to be analyzed for ammonia and nitrate were frozen. Samples were delivered on ice in a cooler to the Deer Island Central Laboratory generally within one week of collection.

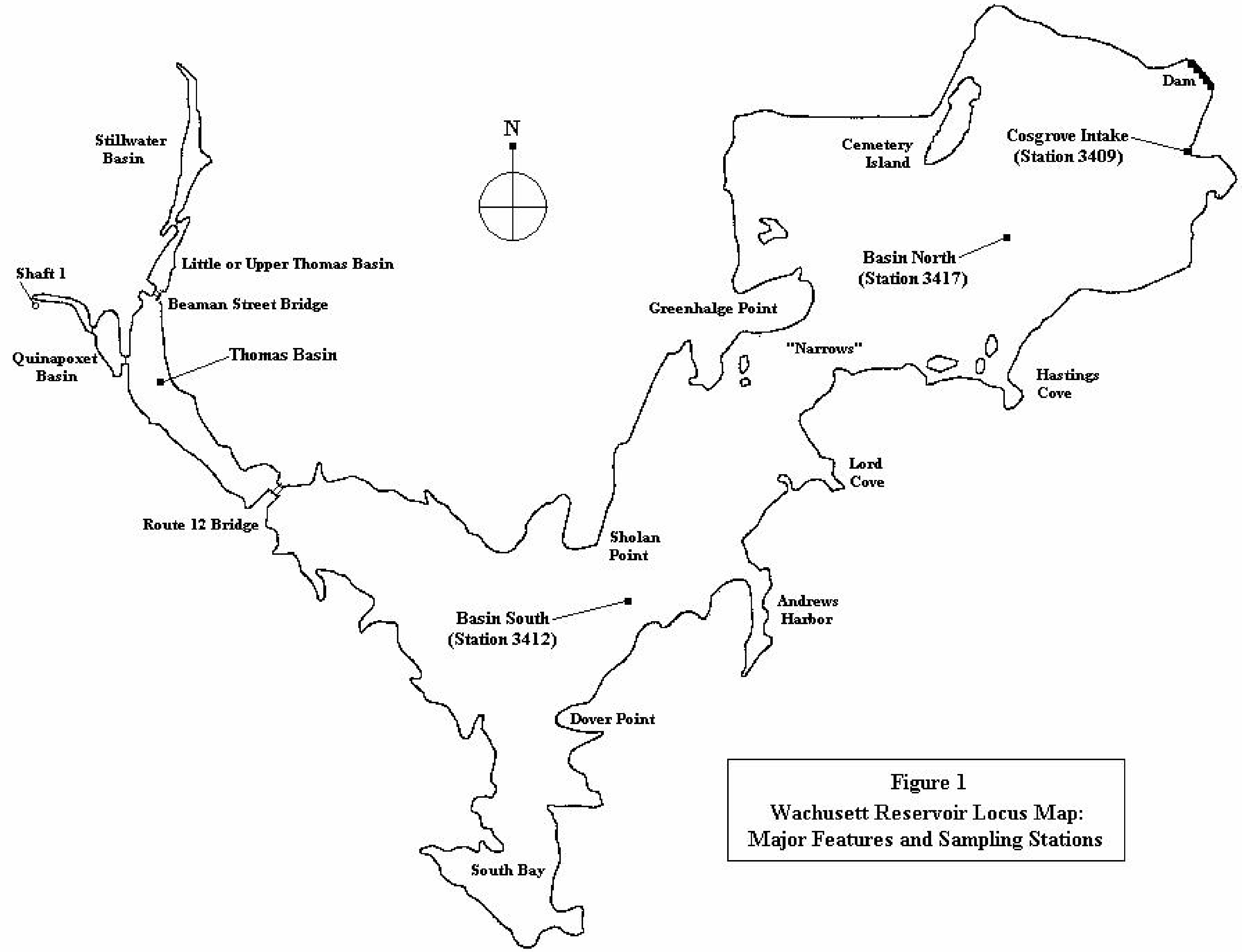

Figure 1
Wachusett Reservoir Locus Map:
Major Features and Sampling Stations

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At the conclusion of monthly sampling in September 1999 a modified program of nutrient monitoring was continued on a quarterly basis according to the following schedule: at the onset of thermal stratification (late April - early May), in the middle of the stratification period (late July), near the end of the stratification period (late October - early November), and during a winter period of mixis before ice cover (December). The quarterly sampling program was also modified to include a lower minimum detection limit for Total Kjeldahl-Nitrogen (reduced to 200 ug/L from 600 ug/L) and the addition of UV254 absorbance among the parameters to be measured. Measurement of UV absorbance at a wavelength of approximately 254 nanometers is a surrogate assay of the concentrations of organic compounds dissolved in the water.

2.2 Plankton

Plankton analysis was a key component of the 1998-99 year of monthly sampling and the field procedures and laboratory methods used are given in Section 2.2.1 below. This report also provides a comprehensive review of the separate DWSP program of weekly plankton sampling conducted, since 1987, off the catwalk at the rear of Cosgrove Intake. Field procedures and laboratory methods associated with the Cosgrove sampling program are presented in Section 2.2.2 below.

2.2.1 Monthly Reservoir Sampling in 1998-99

Taxonomic composition, density, and seasonal dynamics of the plankton community in Wachusett Reservoir were evaluated through a program of monthly sampling at the four sampling stations within the basin (identified in Section 2.1 above). Transparent vinyl tubing (1 inch O.D. x 3/4 inch I.D.) was used to collect depth-integrated samples. The weighted end of the tube was lowered from the surface to a pre-selected depth, the surface end of the tube stoppered to prevent loss of water during tube retrieval, and the tube retrieved with an extracted “core” of the water column. The water in the tube was transferred into a polyethylene bottle (4 liter capacity measuring approximately 30 cm high and 15 cm in diameter) rendering a composite sample of plankton over that depth. Due to the lack of tubing at the time of the initial sampling effort in October 1998, surface grab samples were collected, but these were the only exception to the integration procedure described above.

Integrated samples were generally collected to a depth of 7 or 8 meters, which encompassed the entire epilimnion and its interface with the metalimnetic “interflow” stratum during the period of thermal stratification (see Section 3.0 below). Data from water column profiles of dissolved oxygen and hydrogen ion activity (pH) indicate that most photosynthetic activity occurs in the epilimnion. This sampling depth was maintained during non-stratified conditions to provide consistency in the data.

Samples were preserved in the field with Lugol's Solution (3 ml per 1,000 ml of sample according to Standard Methods) and transported to the lab for processing. Prior to microscopic analysis, all samples were concentrated by a process of sedimentation. This entailed keeping the sample bottles undisturbed for a least one week to allow the organisms to settle to the bottom and then decanting the overlying supernatant in each bottle with a peristaltic pump. The one week minimum sedimentation period surpasses the EPA (1973) guideline of 4 hours per 1 cm depth of sample bottle. Samples were concentrated generally to between 5% and 15% of their original volume by this process. Final results reported for each sample incorporate the appropriate correction factor.

In addition to the quantitative samples of plankton collected with the integrated tube sampler, a net was used to collect qualitative samples of larger forms of phytoplankton and zooplankton. A plankton net of 35 micron mesh was manipulated vertically through the water column at Station 3417 (Basin North) in conjunction with monthly collection of integrated tube samples. The net filters and concentrates plankton from an unknown quantity of water and cannot provide estimates of density, but does enable the relative abundances of the larger forms to be determined.

Microscopic analysis of plankton samples was performed with a compound microscope capable of magnification from 40 to 1,000 times and using phase-contrast illumination. Plankton taxa in the integrated samples were enumerated using a Sedgewick-Rafter (S-R) Cell which enables plankton densities to be quantified. Each concentrated sample was inverted a few times to homogenize the sample and then 1 ml of the sample was withdrawn with a pipette and placed into the S-R Cell. Approximately 15 minutes were allowed for the plankton to settle to the bottom of the S-R Cell before enumeration. Plankton were enumerated in a total of 10 fields described by an ocular micrometer. At 200X magnification, the ocular field measures 0.3136 square millimeters in area (previously calibrated with a stage micrometer) and the fields were selected for viewing at approximately 0.5 cm intervals across the length of the S-R Cell.

Plankton densities were expressed as Areal Standard Units (ASU; equivalent to 400 square microns). The area of each specimen viewed in each counting field was estimated using the ocular micrometer (the ocular field was divided into a 10 by 10 grid, each square in the grid having an area of 3,136 square microns or 7.84 ASU at 200X magnification). In the case of taxa which form gelatinous envelopes or are enclosed in a colonial mucilage, such as *Microcystis*, the area of the envelope was included in the estimate for that specimen. The areal extent of certain colonial taxa, such as the diatoms *Asterionella* and *Tabellaria*, was estimated by measuring the dimensions of one cell and multiplying by the number of cells in the colony. Cell fragments or structures lacking protoplasm, including lorica of *Dinobryon*, diatom frustules, and thecae of dinoflagellates, were not included in the count.

Phytoplankton and zooplankton were generally identified to genus. One exception was copepods which were identified only to suborder (Calanoida or Cyclopoida) at the present time. An effort was made to identify dominant forms of plankton to species. Taxonomic references used to identify plankton are listed at the end of this report (Section 8.0).

2.2.2 Weekly Sampling at Cosgrove Intake from 1987 to 2002

Regular assessments of plankton densities is critical for timely decisions by MWRA on the need for algaecide applications to avoid episodes of rapid population growth ("blooms") by certain organisms that cause unpleasant taste and odors in water supplied to consumers. To meet this need, DWSP staff have collected plankton samples from the catwalk at the rear of Cosgrove Intake once or twice per week since August of 1987, except during periods of ice cover or because of occasional equipment or staff scheduling problems. Discrete grab samples were generally taken from the surface and at depths of 6, 8, 10, 12, and 14 meters using a two-liter Van Dorn Bottle.

In the laboratory, the live plankton in each sample were concentrated from a volume of 500 ml to 12 ml by a process of sand filtration. The method of sand filtration for concentration of live plankton samples has long been in use by both MWRA and DWSP because it enables relatively rapid analysis of samples while subjecting organisms to minimal damage or distortion. The specific method used is documented in Standard Methods Twelfth Edition (1965, pages 669-671; photocopies kindly provided by Warren Zepp of MWRA). In brief, the method entails gravity filtration of sample water placed in a funnel through a layer of fine sand, followed by washing and gentle shaking of the sand with waste filtrate water in a beaker to detach organisms from the sand grains, and lastly, prompt decanting of the concentrated sample after the sand has been allowed to settle.

A 1 milliliter aliquot of each concentrated sample was then analyzed microscopically in a S-R Cell using quantitative techniques similar to those documented in Section 2.2.1 above. As these samples contained living organisms, the underside of the coverslip on the S-R Cell was scanned to observe any floating cyanophytes (mainly *Anabaena*) or mobile chrysophytes (*Synura*, *Uroglenopsis*, *Chrysosphaerella*, and *Dinobryon*). Detection of mobile colonial forms of phytoplankton was enhanced by using a stereozoom dissecting microscope to scan the entire S-R Cell prior to enumeration using a compound microscope. To facilitate prompt analysis of samples, only chrysophytes were quantified in samples collected at depths of 6, 10, and 12 meters and in a second set of samples collected in any week due to the propensity of members of this taxon for triggering consumer complaints about unpleasant taste and odors.

3.0 THERMAL STRATIFICATION, THE QUABBIN INTERFLOW, AND NUTRIENT DISTRIBUTION IN WACHUSETT RESERVOIR

Typical of most deep lakes and reservoirs in the temperate region, Wachusett Reservoir becomes thermally stratified in summer. In Wachusett Reservoir, this structure is accentuated by the Quabbin "interflow," a hydrodynamic phenomenon resulting from the annual transfer of water from Quabbin Reservoir to Wachusett via the Quabbin Aqueduct (see below). The thermal structure of the Wachusett water column and the presence of the interflow stratum were major determinants of the vertical distribution of many nutrients measured during the summer and fall periods of the sampling program.

The Quabbin transfer has a profound influence on all functional characteristics of Wachusett Reservoir including hydrodynamics, annual water and nutrient budgets, and stratification structure. During the years 1995 through 2002, the amount of water transferred annually from Quabbin to Wachusett ranged from a volume equivalent to 44 percent of the Wachusett basin up to 94 percent. The period of peak transfer rates generally occurs from June through November. However, at any time of the year, approximately half of the water in the Wachusett basin is derived from Quabbin Reservoir. A brief overview of the process of thermal stratification, the Quabbin interflow, and their influence on nutrient distribution is given below.

3.1 Thermal Stratification and the Quabbin Interflow

Solar radiation and atmospheric warming in spring and summer cause a progressive gain of heat in surficial waters and the formation of a thermal gradient in the water column. The thermally stratified water column of summer is characterized by a layer of warm, less dense water occupying the top of the water column ("epilimnion"), a stratum of cold, dense water at the bottom ("hypolimnion"), and a middle stratum exhibiting a pronounced temperature gradient ("metalimnion").

The period of peak transfer of water from Quabbin Reservoir to Wachusett via the Quabbin Aqueduct overlaps the period of thermal stratification in both reservoirs. Water entering the Quabbin Aqueduct at Shaft 12 is withdrawn from depths of 13 to 23 meters in Quabbin Reservoir. These depths are near or within the hypolimnion of Quabbin Reservoir where water temperatures range from only 9 to 13 °C in the period June through October.

This deep withdrawal from Quabbin is colder and denser relative to epilimnetic waters in Wachusett Reservoir. However, after being discharged at Shaft 1 (Figure 1), the transfer water gains a slight amount of heat from mixing as it passes through Quinapoxet Basin and Thomas Basin and is not as cold and dense as the hypolimnion of Wachusett. Therefore, Quabbin water transferred during the period of thermal stratification flows conformably into the metalimnion of Wachusett where water temperatures and densities coincide. The term interflow (Wetzel, 1983) describes this metalimnetic flow path for the Quabbin transfer. The interflow develops gradually during the period of transfer and eventually occupies the stratum between depths of approximately 6 to 15 meters in the Wachusett water column.

Interflow water quality is distinctive from ambient Wachusett water having lower specific conductivity and lower concentrations of all nutrients characteristic of Quabbin Reservoir (see Section 4.0 below). Multiprobe measurements of conductivity readily distinguish the flow path of Quabbin water as it is transferred to Wachusett. Thomas Basin is progressively "flushed out" while, in the main basin, the interflow becomes conspicuous in profile measurements as a metalimnetic stratum of low conductivity (Figure 2). The profile "trough" of low conductivity values intensifies (extends to lower values) over the period of transfer as water in the interior of the interflow undergoes less mixing with ambient reservoir water at the boundaries of the interflow stratum.

The presence of the Quabbin interflow is also evident in temperature profiles as a pronounced flattening or plateau in the thermocline generally between 9 and 13 meters where the temperatures generally center around 13 to 14 °C. This temperature plateau coincides with minimum conductivity values and represents the "core" of the interflow stratum that undergoes minimal mixing with ambient Wachusett water. Profile data from 1999 confirm that the interflow is a gravity-driven phenomenon spreading through the metalimnion into all portions of the basin having sufficient depth including South Bay, Andrews Harbor, west of Cemetery Island, and against the dam.

Analysis of timing and volumes required for interflow penetration across the reservoir based on recent transfers from Quabbin indicate that it takes about 3 to 5 weeks and from 5.5 to about 7.8 billion gallons of transfer discharge for the interflow to reach Cosgrove Intake (Table 2; the transfer in 1995 was exceptional as explained below). The rate of interflow penetration through the reservoir system depends on the timing and intensity of transfer from Quabbin. A regression of average transfer rate as the independent variable against penetration interval (defined by initial detection of decreased conductivity in water column profiles measured at or near Cosgrove Intake) confirms the significance of a predictable relationship: higher transfer rates result in shorter time intervals for interflow penetration (Figure 3).

The exceptions to linearity in the regression are for 1999 and 2000 when the average transfer rate for both years was 243 mgd, but transfer was initiated on May 3, 1999 and June 28, 2000. These deviations are instructive as to the influence of transfer timing. The regression predicts a slower penetration interval for 2000 and a faster one for 1999 with the same transfer rate. This indicates that interflow penetration is delayed by mixing within a weakly stratified water column when transfer is initiated early in the year such as in 1999. The leading edge of the interflow generally penetrates relatively high in the water column (6 to 11 meters) and, unless constantly replenished, is susceptible to dispersion through radiant heat gain and mixing by wind-induced turbulence.

Conversely, penetration is enhanced later in the year when a pronounced thermal structure has developed that is more resistant to mixing (such as in 2000). When a sharp thermal gradient has developed in the Wachusett water column, water transferred from Quabbin undergoes less mixing with ambient reservoir water at the leading edge and boundaries of the interflow stratum. The most extreme example of mixing was in 1995 when transfer was initiated very early on April 14, but penetration was prolonged to 63 days despite a robust average transfer rate of 231 mgd (the regression depicted in Figure 3 excludes the 1995 data for this reason).

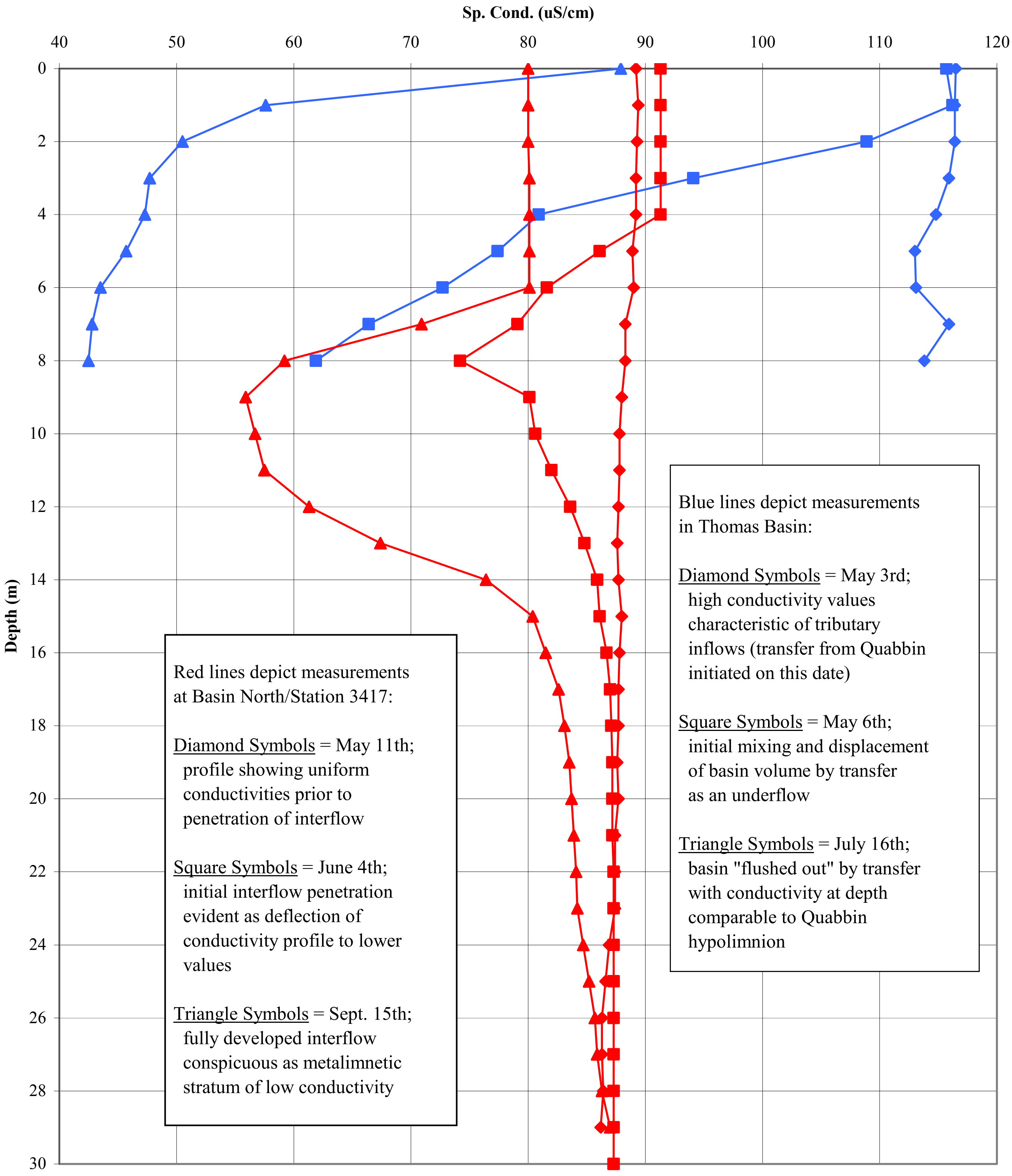
As a gravity-driven phenomenon, efficient penetration of the water column by the interflow requires a steady inflow of cold transfer water to maintain momentum in the main basin as it spreads through the metalimnion. Although water withdrawal may induce some movement of metalimnetic water in close proximity to Cosgrove Intake, the interflow is not a plug or layer of water being "pulled" by demand at Cosgrove. The momentum of interflow penetration is derived from a prolonged input of cold transfer water at rates of around 250 mgd. Efficient penetration requires that this "push from behind" be continuous and, depending on the date of transfer initiation, amount to a total of between 5.5 to 7.8 billion gallons of transfer inflow.

In addition to forming the interflow, Quabbin transfer water spreads out over the bottom of Quinapoxet Basin and Thomas Basin as a cold, dense underflow. Eventually this underflow "flushes out" and displaces most of the volume in these basins except for a relatively thin surface layer of warm water derived from tributary runoff (Figure 2). Profile data from 1999 demonstrate that this "basement" stratum of cold water can penetrate "upstream" into the upper reaches of the reservoir system as far as the railroad bridge that forms the bottleneck between Stillwater Basin and Upper Thomas Basin.

During periods of peak transfer, a remarkable manifestation of strong Quabbin underflow moving through Thomas Basin into the main basin becomes evident at the bottleneck formed by the Route 12 Bridge. The cold underflow through this bottleneck induces a counter-current of warm surface water moving from the main basin "upstream" back into Thomas Basin (best observed on a windless day). Profiles recorded downgradient of the Route 12 Bridge indicate that the underflow exiting Thomas Basin becomes an interflow spreading out over colder ambient water upon reaching a location in the main basin where depths are sufficient to accommodate hypolimnetic extremes of water temperature and density (approximately 250 meters downgradient of the Route 12 Bridge).

Once established, the interflow essentially connects Quabbin inflow to Cosgrove Intake in a metalimnetic "short circuit" undergoing minimal mixing with ambient Wachusett Reservoir water. The interflow stratum exhibits a thermal gradient characteristic of its metalimnetic position and separates ambient Wachusett water composing the epilimnion and hypolimnion.

Figure 2 - Quabbin Transfer and Interflow Development in 1999: Profiles in Thomas Basin and at Basin North/Station 3417



Blue lines depict measurements in Thomas Basin:

<u>Diamond Symbols</u> = May 3rd; high conductivity values characteristic of tributary inflows (transfer from Quabbin initiated on this date)

<u>Square Symbols</u> = May 6th; initial mixing and displacement of basin volume by transfer as an underflow

<u>Triangle Symbols</u> = July 16th; basin "flushed out" by transfer with conductivity at depth comparable to Quabbin hypolimnion

Red lines depict measurements at Basin North/Station 3417:

<u>Diamond Symbols</u> = May 11th; profile showing uniform conductivities prior to penetration of interflow

<u>Square Symbols</u> = June 4th; initial interflow penetration evident as deflection of conductivity profile to lower values

<u>Triangle Symbols</u> = Sept. 15th; fully developed interflow conspicuous as metalimnetic stratum of low conductivity

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Table 2 - Transfer Timing, Volumes, and Rates Associated with Interflow Penetration through Wachusett Reservoir

Transfer Year	Date of Transfer Initiation	Estimated Date of Interflow Arrival at Cosgrove*	Time Required for Interflow Penetration	Volume Transferred During Penetration Interval	Average Rate of Transfer During Penetration Interval
1995	April 14th	June 15th	63 days	14.5 bg	231 mgd
1996	June 14th	July 10th	27 days	6.90 bg	256 mgd
1997	June 9th	July 6th	28 days	6.97 bg	249 mgd
1998	July 20th	August 7th	19 days	5.45 bg	287 mgd
1999	May 3rd	June 4th	33 days	8.02 bg	243 mgd
2000	June 28th	July 19th	22 days	5.35 bg	243 mgd
2001	May 16th	July 2nd	48 days (low and erratic transfer rates)	8.48 bg	177 mgd
2002	June 13th	July 17th	35 days	7.78 bg	222 mgd

* estimate based on initial detection of decreased conductivity in water column profiles measured off Cosgrove Intake (Station 3409)

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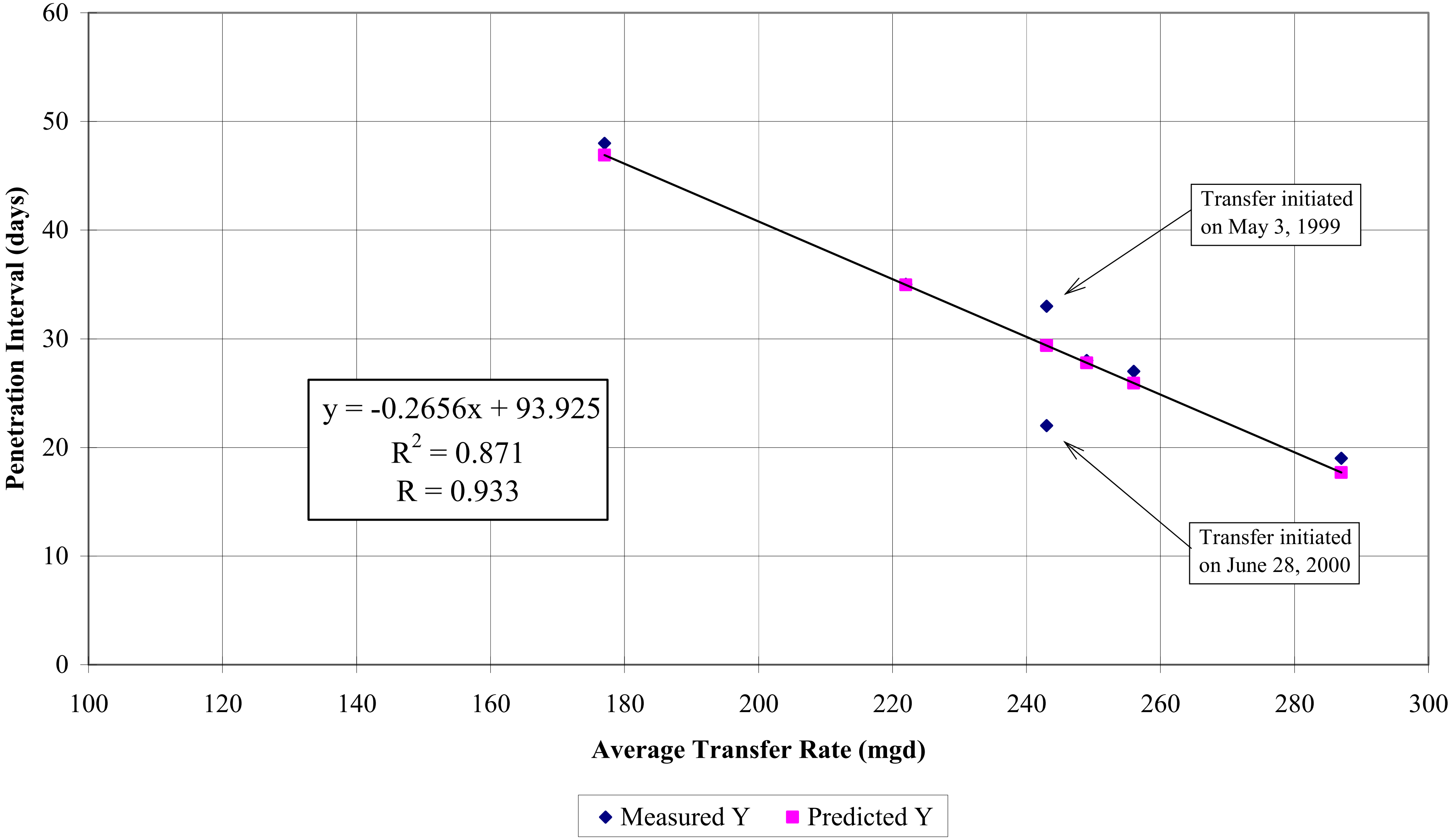
Figure 3 - Regression of Average Transfer Rate on Interflow Penetration Interval



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3.2 Thermal Stratification and Nutrient Distribution

Waters of the epilimnion circulate due to wind acting on the surface, whereas waters of the hypolimnion are isolated from atmospheric influences by the stratification structure and remain relatively undisturbed. Most photosynthetic activity by phytoplankton occurs in the epilimnion and upper metalimnion where light intensity is greatest and, especially in the epilimnion, where plankton is recirculated toward the surface by wind-driven turbulence (Section 5.0 below). Due to the predominance of photosynthetic production in the epilimnion it generally comprises what is termed the trophogenic zone (zone of net organic synthesis).

In contrast, the predominant process in the hypolimnion is decomposition of organic matter. Planktonic organisms and detritus sinking down from overlying strata into the hypolimnion are not recirculated. The constant "rain" of sedimenting organic matter reaching the dark, quiescent waters of the hypolimnion is broken down via microbial respiration. As a result of the ascendancy of this process, the hypolimnion generally composes what is termed the tropholytic zone (zone of net organic decomposition).

The boundary between the trophogenic and tropholytic zones is a function of light intensity with the term "compensation level" applied to the depth at which photosynthetic production is matched by decomposition. Water column profiles of dissolved oxygen and hydrogen ion activity (pH) measured with a multiprobe document the relative intensities of the processes occurring in these zones.

In the epilimnion and upper metalimnion (approximately the trophogenic zone), dissolved oxygen remains near saturation concentrations throughout the stratification period due to releases of oxygen from photosynthetic organisms. Also, photosynthetic uptake of carbon dioxide tends to increase pH and values in the epilimnion and upper metalimnion remain near neutral throughout the stratification period, generally ranging between values of 6.5 and 7.5.

Conversely, in the hypolimnion and lower metalimnion (approximately the tropholytic zone), dissolved oxygen concentrations decrease due to demand by the oxidizing processes of decomposition and respiration. Minimum values ranging as low as 40 percent saturation are reached in the latter part of the stratification period (late October). The production of carbon dioxide by microbial respiration tends to decrease pH and, by the end of the stratification period, hypolimnetic pH reaches minimum values generally ranging between 5.3 to 5.9.

Multiprobe measurements within the metalimnetic interflow confirm that, except for the upper portion of this stratum near the boundary with the epilimnion, dissolved oxygen concentrations and pH values decline during the stratification period. These reductions in dissolved oxygen and pH within the interflow are mainly indicative of decomposition processes occurring within the hypolimnion of Quabbin Reservoir rather than within the water column of Wachusett Reservoir.

Measurements of Secchi transparency indicate that much of the interflow stratum receives light at intensities adequate to support photosynthesis and net productivity (greater than a minimum of about 1% of incident surface light; generally considered to be present at a depth of twice the Secchi value). However, it is likely that movement of phytoplankton from the epilimnion downward into the metalimnetic interflow is restricted by the steep thermal and density gradients at the interface between these strata. The inability of phytoplankton to inoculate or disperse into the metalimnetic interflow much beyond the epilimnetic boundary relegates most of the interflow stratum to the tropholytic conditions transferred from Quabbin despite the availability of sufficient illumination for photosynthesis.

The presence of the interflow stratum and the antagonistic processes occurring in the trophogenic and tropholytic zones determine patterns of nutrient distribution vertically in the water column (Section 4.0 below). In particular, the contrast between epilimnion and hypolimnion becomes pronounced in the latter part of the stratification period.

However, in late fall after heat is lost from the upper portion of the water column, the thermal gradient becomes weak and the stratification structure is eventually dispersed by wind-driven turbulence. In Wachusett Reservoir, the breakdown of stratification structure initially involves the epilimnion and metalimnetic interflow stratum with wind energy homogenizing the water column down to a depth of around 15 meters.

Within a week or two of this initial mixing, wind energy disperses the remnant stratification pattern associated with the hypolimnion and mixes the entire water column in an event known as fall "turnover." Turnover results in a water column that is isothermal and thoroughly mixed (generally occurring in late October or early November). Subsequent to fall turnover and during ice-free periods of water column isothermy and mixing (generally November through mid-January and late March through April), all stations exhibit nutrient concentrations that are similar throughout the water column.

4.0 RESULTS OF NUTRIENT ANALYSES

The 1998-99 program of monthly sampling provided a detailed record of seasonal patterns in the distribution of nutrients in Wachusett Reservoir. Quarterly sampling conducted since the conclusion of the monthly program confirmed the consistency of these seasonal patterns from one year to the next, but also documented shifts in nutrient concentrations and parameter intensities between years resulting from the interaction of the Quabbin transfer and watershed inputs.

4.1 Seasonal Patterns: Monthly Data from 1998-99

Results from the monthly sampling program confirm that Wachusett Reservoir is an oligotrophic system characterized by low rates of nutrient input and biological productivity (Table 3, also see complete database in Appendix A). Concentrations of all nutrients and patterns of season fluctuation were similar across all sampling stations in the main basin of the reservoir (Cosgrove Intake/Station 3409, Basin North/Station 3417, and Basin South/Station 3412) except in the hypolimnion at Cosgrove Intake.

Table 3 - Summary of Laboratory Results for Sampling Program Conducted from October, 1998 through September, 1999

Parameter	Range of Medians in Epilimnion/Surface of Main Basin	Range of Medians in Metalimnion of Main Basin	Range of Medians in Hypolimnion/Bottom of Main Basin	Range of Medians from All Depths in Thomas Basin
Total Phosphorus (ug/L)	6	6	6 - 7	6 - 9
Ammonia Nitrogen (ug/L)	<5 - 6	<5 - 6	7 - 12	<5 - 6
Nitrate Nitrogen (ug/L)	46 - 75	19 - 26	75 - 111	6 - 27
Total Inorganic Nitrogen (ug/L)	53 - 83	24 - 32	83 - 132	11 - 40
Total Kjeldahl Nitrogen (mg/L)	<0.6	<0.6	<0.6	<0.6
Silica (mg/L)	2.20	1.52 - 1.68	2.16 - 2.84	1.34 - 1.77
Alkalinity (mg/L as $CaCO_3$)	5.38 - 5.51	4.48 - 4.89	5.11 - 5.28	4.29 - 5.23

TROPHIC STATE CRITERIA
(epilimnetic values; from Wetzel, 1983)

Trophic Category	Total Phosphorus	Total Inorganic Nitrogen
ultra-oligotrophic	<5 ug/L	<200 ug/L
oligo-mesotrophic	5 - 10 ug/L	200 - 400 ug/L

At Cosgrove Intake the maximum depth is 16 meters and thus, during the period of stratification, deep grab samples are collected at the boundary between the metalimnetic interflow and the hypolimnion. Additionally, there exists a submerged dike that was constructed as the foundation of a coffer dam during installation of Cosgrove Intake. Water drawn toward the intake at depth flows over this dike thereby causing waters of the hypolimnion to be mixed with the interflow. As a result of the above factors, seasonal patterns in hypolimnetic nutrient concentrations are obscured at Cosgrove Intake with relatively dilute hypolimnetic concentrations being measured in comparison to those documented at Basin North (Station 3417) and Basin South (Station 3412).

In Thomas Basin, concentrations of all parameters were relatively low during the extended periods of transfer from Quabbin that overlapped the year of study (July, 1998 through February, 1999 and May through December, 1999; see Table 3). However, concentrations of all nutrients except ammonia shifted to higher ranges during the brief non-transfer period (March and April, 1999) when discharges from the Quinapoxet and Stillwater Rivers were the predominant loading sources (Table 4).

Table 4 - Influence of the Quabbin Transfer on Thomas Basin

Parameter	**Range of Concentrations at All Depths During Transfer Periods**	**Range of Concentrations at All Depths During Non-Transfer Period**
Total Phosphorus (ug/L)	<5 - 17.8	9.8 - 21.8
Ammonia-Nitrogen (ug/L)	<5 - 15.3	<5 - 6.2
Nitrate-Nitrogen (ug/L)	<5 - 54.7	135 - 177
Total Inorganic Nitrogen (ug/L)	<10 - 61	140 - 183
Silica (mg/L)	1.26 - 3.06	3.14 - 5.00

In the main reservoir basin, seasonal and vertical fluctuations in nutrient concentrations provided the most pronounced patterns in the distribution of nutrients over the year of study. Minimum concentrations of many nutrients occurred during the summer growing season of phytoplankton (Section 5.0 below). Specifically, phytoplankton demand for ammonia was evident when the onset of seasonal low concentrations occurred in April (Figure 4) and demand for nitrate and silica evident with the onset of seasonal low concentrations in July (Figures 5 and 6 respectively).

Superimposed on the affect of seasonal demand by phytoplankton for nutrients, the presence of the Quabbin interflow is evident in the range of relatively low metalimnetic concentrations of nitrate, silica, and alkalinity (Table 3). Results for the nitrogen species (ammonia, nitrate, and total Kjeldahl-nitrogen), silica, total phosphorus, and alkalinity in the main reservoir basin are discussed separately in the sections that follow.

4.1.1 Nitrogen

The onset of seasonal low concentrations of ammonia and nitrate began in April and July respectively as a result of demand by phytoplankton (Figures 4 and 5). Supplies of ammonia were depleted throughout the trophogenic zone (samples collected in the epilimnion) with concentrations generally remaining near or below the detection limit of 5 ug/L through September. Similarly, in the period July through September, epilimnetic concentrations of nitrate were below the detection limit of 5 ug/L.

Depletion of these nutrients in the trophogenic zone is indicative of productivity by phytoplankton (Section 5.0 below). Phytoplankton growing in this zone extracted ammonia and nitrate and incorporated them into their organic constituents as amino nitrogen. Many phytoplankton growing in the trophogenic zone eventually sank down into the hypolimnion where they could not be recycled upward in the water column by wind-driven mixing. The processes of nutrient uptake and sedimentation by phytoplankton functioned to remove ammonia and nitrate from the trophogenic zone more rapidly than they were replaced by inputs to the reservoir.

Hypolimnetic concentrations of ammonia and nitrate increased during the summer while epilimnetic concentrations of these nutrients remained depressed (Table 3 and Figures 4 and 5). This vertical gradient in nutrient concentrations was the result of decomposition of organic material (mostly phytoplankton) sedimenting out from overlying waters into the tropholytic zone. Microbial decomposition of sedimenting organic material generated ammonia. Much of this ammonia was oxidized to nitrate in a process known as nitrification mediated by chemoautotrophic bacteria (bacteria that derive energy from the oxidation of inorganic compounds).

As a result of the above processes, both ammonia and nitrate accumulated in the hypolimnion during the summer and fall period of thermal stratification (Figures 4 and 5; this pattern is obscured at Cosgrove Intake as discussed above). These accumulated nutrients were mixed into the entire water column between the October and November sampling dates during fall turnover.

Concentrations in the November through April period of mixing were generally intermediate between the extremes of summer epilimnetic depletion and hypolimnetic accumulation. Some of the ammonia and nitrate measured in the water column during this time was recycled from the hypolimnion at fall turnover. Generally, these intermediate concentrations reflect loading rates from the watershed and atmosphere in the absence of intense seasonal demand by phytoplankton. At all stations and depths throughout the year, including Thomas Basin, the combined concentrations of ammonia and nitrate (total inorganic nitrogen or TIN) are below the "ultra-oligotrophic" category threshold of 200 ug/L identified by Wetzel (1983).

Concentrations of total Kjeldahl-nitrogen (TKN; organic forms of nitrogen plus ammonia) were generally less than the detection limit of 0.60 mg/L throughout the year at all stations and depths, including Thomas Basin (Table 3). Specifically, 78 percent of all samples had TKN concentrations less than the detection limit. Concentrations of TKN in all samples collected in December were elevated in comparison to results for all other months and appear to represent an isolated incident of sample bottle contamination or laboratory error.

4.1.2 Silica

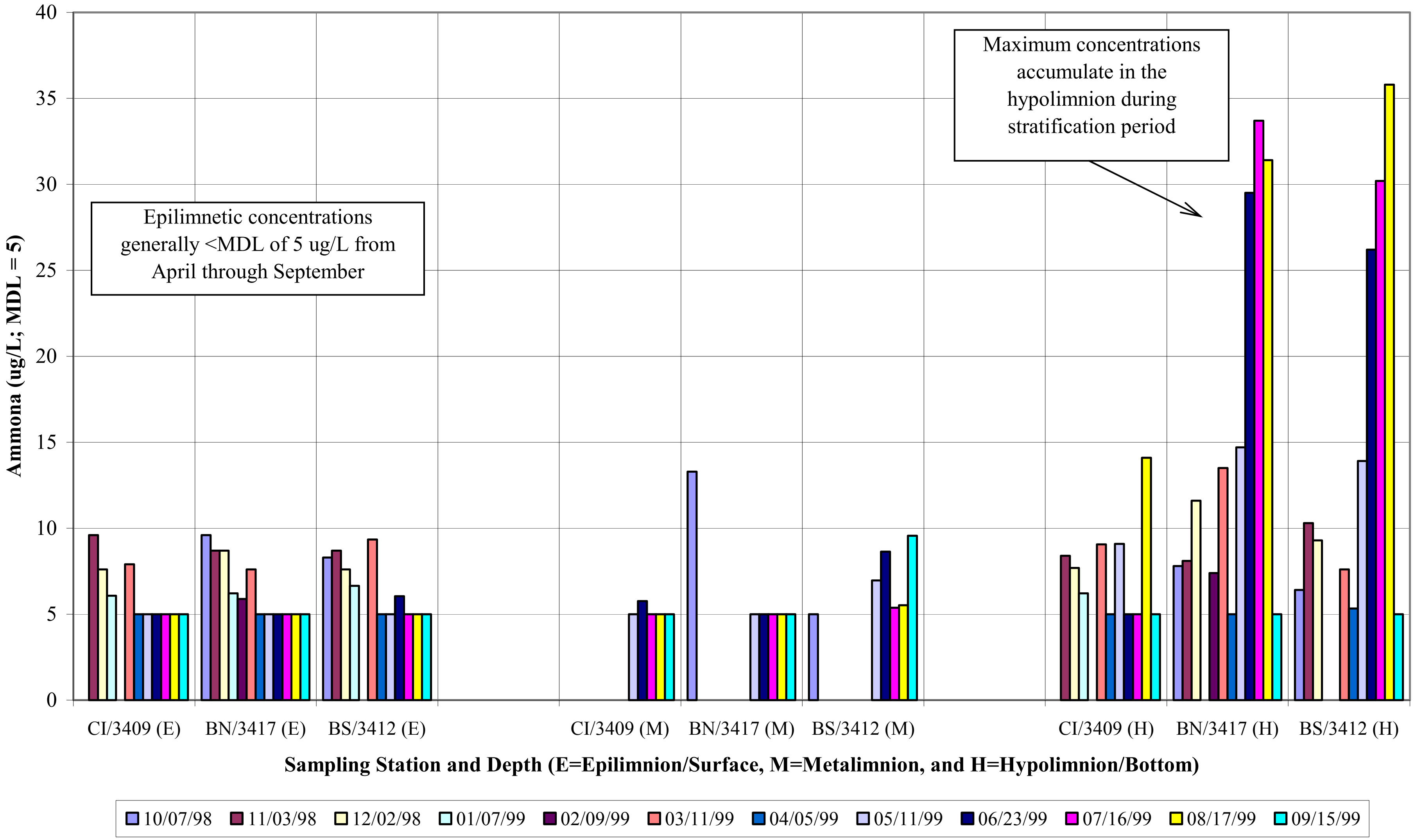
Silica is a unique nutrient because, among major groups of phytoplankton, it is essential only to diatoms (some chrysophyte genera also require silica). All diatom species build an enclosing wall or frustule using silica extracted from the surrounding water. Demand for silica by diatoms was evident with the onset of seasonal low concentrations in July (Figure 6). Diatoms growing in the trophogenic zone (Section 5.0 below) assimilated silica and many eventually sank down into the hypolimnion as described above in Section 4.1.1. The processes of diatom growth and sedimentation functioned to remove silica from the trophogenic zone more rapidly than it was replaced by inputs to the reservoir. Minimum concentrations in the trophogenic zone (samples collected in the epilimnion) ranged from 1.26 to 1.46 mg/L in the period July through September. The presence of the interflow is evident in the relatively low metalimnetic concentrations of silica which are characteristic of the Quabbin hypolimnion (Table 3).

In contrast to minimum concentrations in the trophogenic zone, maximum concentrations of silica were measured in the hypolimnion during the summer and fall period of thermal stratification (Figure 6; this pattern is obscured at Cosgrove Intake as discussed above). These higher concentrations resulted from the presence of sedimenting diatom frustules in the hypolimnion. Many of these sedimenting frustules were in the process of dissolution as diatoms decomposed in the tropholytic zone. As a result of this process, silica accumulated in the hypolimnion reaching maximum values of 3.92 mg/L (Basin North) and 3.74 mg/L (Basin South) in October, 1998. In 1999, during the latter half of the year of study, hypolimnetic silica concentrations trended upward beginning in May reaching concentrations of 3.42 mg/L (Basin North) and 3.17 mg/L (Basin South) at the conclusion of the program in September.

The homogenizing effect of fall turnover is evident in the silica concentrations measured in November, which were similar from top to bottom. As with ammonia and nitrate (Section 4.1.1 above), silica concentrations in the November through April mixing period were intermediate between the summer extremes of depletion in the trophogenic zone and accumulation in the tropholytic zone.

Despite the seasonal lows in the trophogenic zone, concentrations of silica were consistently above 0.5 mg/L which is a threshold below which diatoms generally decline in the plankton community (Wetzel, 1983). In Laurel Lake, a eutrophic hardwater lake located in the Berkshires, a large population of diatoms was observed to bloom in May and reduce silica concentrations to less than 0.1 mg/L before collapsing (Soukup, 1974).

Figure 4 - 1998-99 Nutrient Measurements: Seasonal and Vertical Pattern of Ammonia Concentrations



Epilimnetic concentrations generally <MDL of 5 ug/L from April through September

Maximum concentrations accumulate in the hypolimnion during stratification period

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Figure 5 - 1998-99 Nutrient Measurements: Seasonal and Vertical Pattern of Nitrate Concentrations

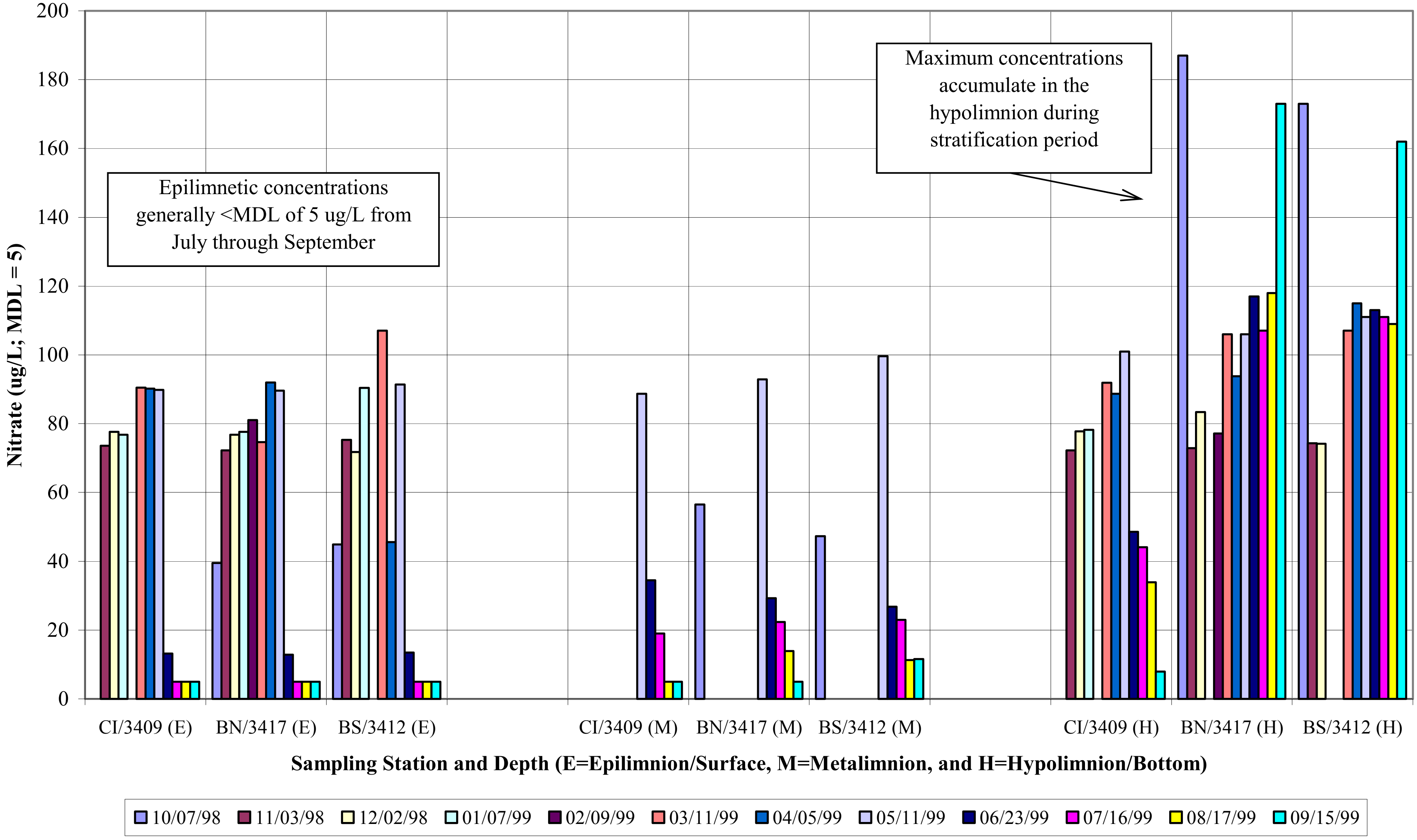

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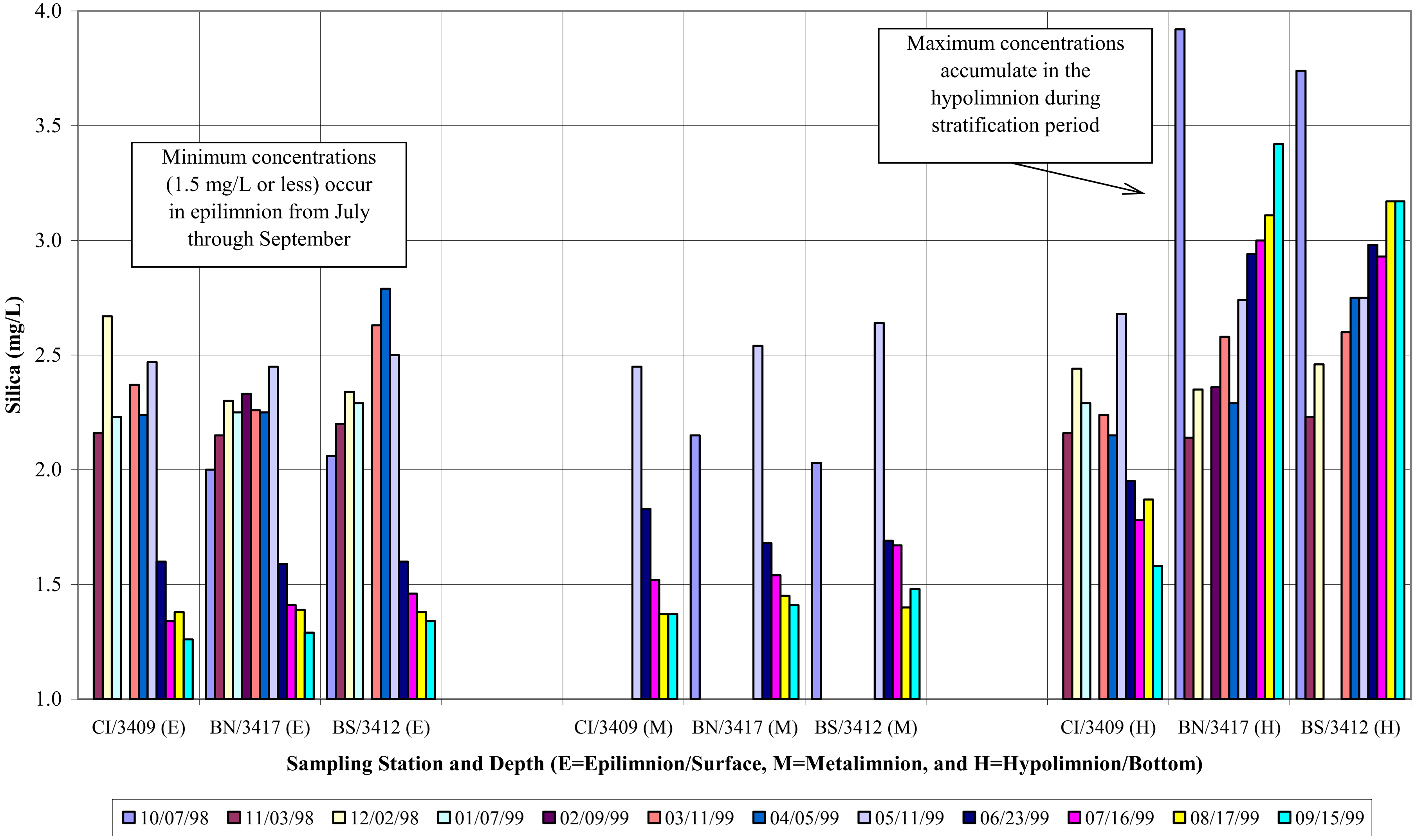
Figure 6 - 1998-99 Nutrient Measurements: Seasonal and Vertical Pattern of Silica Concentrations



Minimum concentrations (1.5 mg/L or less) occur in epilimnion from July through September

Maximum concentrations accumulate in the hypolimnion during stratification period

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The rate of silica loading to the reservoir is mainly determined by natural weathering of aluminosilicate minerals in the watershed (Wetzel, 1983) and is delivered almost exclusively in surface runoff and groundwater. Silica is not a significant constituent of atmospheric precipitation (Soukup, 1974).

4.1.3 Total Phosphorus

In contrast to the seasonal fluctuations of ammonia, nitrate, and silica described above, concentrations of total phosphorus were low throughout the year at all stations and depths with levels generally ranging from below the detection limit of 5 ug/L up to 10 ug/L (Table 3). The median epilimnetic concentration of total phosphorus at all stations, including Thomas Basin, was 6 ug/L. This concentration registers at the lower end of the range defining the "oligo-mesotrophic" category of Wetzel (1983; see Table 3). Demand for phosphorus was particularly acute during the summer growing season of phytoplankton with concentrations reduced to near or below the detection limit of 5 ug/L from June through September generally throughout the water column.

The consistently low concentrations reflect the constant demand for this nutrient by phytoplankton and indicate that phosphorus is the nutrient limiting phytoplankton growth (Section 5.0 below). Limitation of phytoplankton productivity by a short supply of phosphorus relative to other nutrients is typical of most temperate lakes and reservoirs.

4.1.4 Alkalinity

Although not a nutrient, alkalinity is a measure of the capacity of water to buffer changes in hydrogen ion activity (pH) and also provides an indication of the availability of dissolved inorganic carbon (free carbon dioxide, bicarbonate, and carbonate). Dissolved inorganic carbon is essential for photosynthesis and, under conditions of short supply, has been shown to favor growth by cyanophytes ("blue-green algae" or cyanobacteria) over other phytoplankton. However, nuisance growth by cyanophytes is generally limited to nutrient-rich systems at the opposite end of the trophic spectrum from Wachusett Reservoir.

The concentrations of alkalinity measured in the reservoir represent a low buffering capacity typical of softwater systems. However, fluctuations in pH were not extreme and corresponded to seasonal processes occurring in the stratified water column (discussed in Section 3.0 above). The presence of the Quabbin interflow is evident in the relatively low metalimnetic concentrations of alkalinity (Table 3). Measured concentrations of alkalinity were quite stable throughout the year of study showing minimal seasonal variability. Median concentrations at all stations and depths, including Thomas Basin, ranged from 4.29 to 5.51 mg/L as $CaCO_3$ (Table 3).

4.2 Interannual Patterns: Quarterly Data Through 2002

Nutrient concentrations in Wachusett Reservoir are influenced by a variety of factors that fluctuate annually. These include amounts of runoff discharged from the watershed (derived from rain and snowmelt), nutrient loading rates associated with runoff from various land uses, and population dynamics of phytoplankton. Overriding these factors however, is the timing and duration of the Quabbin transfer. Water quality within the reservoir basin reflects a dynamic interaction between the influence of the Wachusett watershed and the influence of the Quabbin transfer. The Quabbin transfer is characterized by water of very low nutrient concentrations whereas the influence of the Wachusett watershed is exerted mostly via the discharges of the Quinapoxet and Stillwater Rivers with higher nutrient concentrations. The interplay between these two influences causes the ranges of nutrient concentrations and parameter intensities to shift from one year to the next as discussed in the following sections.

4.2.1 Influence of Delayed Quabbin Transfer: Data from 2000

Results of quarterly nutrient sampling in 2000 document concentrations that generally registered within or close to the ranges observed in the 1998-99 year of monthly sampling (see complete quarterly database in Appendix B). However, some of the values of nitrate, ammonia, silica, and total phosphorus measured in 2000 were notable in registering higher than the ranges observed in the 1998-99 database. Most of these higher values were measured in the May 2000 samples. The occurrence of these higher values in May is significant for identifying a probable explanation.

Historically, the peak period of transfer from Quabbin consists of July, August, and September each year, but it has been initiated as early as May and has extended through December or even into the initial months of the next year. In a year with early initiation of the Quabbin transfer, such as 1999 when the transfer started on May 3rd, nutrient concentrations will range lower due to the greater proportion of Quabbin derived water occupying the basin. At the conclusion of 1999, the transfer volume totaled 225 million cubic meters, equivalent to 90 percent of the Wachusett basin volume.

Conversely, in a year such as 2000 when the transfer was not initiated until June 28th, nutrient concentrations will range higher as discharges from the Quinapoxet and Stillwater Rivers have greater proportional influence. At the conclusion of 2000, the transfer volume totaled 179 million cubic meters, equivalent to 71 percent of the Wachusett basin volume. The relatively elevated concentrations observed in May 2000 reflect a stronger watershed influence because of the late entry and diminished proportion of Quabbin water in the basin compared to 1999.

Other than the slight expansion in the ranges of nutrient concentrations in 2000 discussed above, the seasonal and vertical patterns in the distribution of nutrients from quarterly samples were comparable to those documented in the 1998-99 database (Section 4.1 above).

4.2.2 Influence of Large Watershed Inputs: Data from 2001

Results of quarterly nutrient sampling in 2001 document April concentrations of nitrate, silica, total phosphorus, and UV254 absorbance that register higher than the ranges documented in the 1998-2000 database (see complete quarterly database in Appendix B). Elevated springtime nutrient concentrations were also observed in 2000 when samples collected in May generally had concentrations that registered among the highest observed all year (Section 4.2.1 above). This pattern of relatively high nutrient concentrations in spring followed by lower concentrations the remainder of the year (except for hypolimnetic concentrations in summer; see Section 4.1 above) again reflects the divergent influences of the Wachusett watershed and the Quabbin transfer.

As discussed in Section 4.2.1 above, the year 2000 was characterized by a relatively late transfer from Quabbin and nutrient concentrations ranged higher, especially in May, as discharges from the Quinapoxet and Stillwater Rivers had greater proportional influence. Similarly, in 2001, an exceptionally wet spring intensified nutrient loading from the Quinapoxet and Stillwater Rivers resulting in maximum concentrations recorded on April 26th prior to initiation of the Quabbin transfer on May 16th.

The dominant influence of the Quinapoxet and Stillwater Rivers in the spring of 2001 was especially evident in the form of pronounced horizontal gradients (between sampling locations across the reservoir) in the concentrations of nitrate and silica, in UV254 absorbance, and specific conductance (Table 5).

Table 5 - Lateral Gradients in Ranges of Parameter Values Measured on April 26, 2001

Sampling Locations (all depths) and Parameters	**Thomas Basin**	**Basin South (Station 3412)**	**Basin North (Station 3417)**
	>>>>> increasing distance from river inlets >>>>>		
Nitrate (ug/L)	201 - 236	172 - 192	124 - 138
Silica (mg/L)	4.94 - 4.99	3.84 - 4.13	3.02 - 3.31
UV254 (Absorbance/cm)	0.121 - 0.141	0.085 - 0.091	0.059 - 0.066
Specific Conductance (uS/cm)	121.7 - 136.3	101.2 - 104.2	90.2 - 94.1

The highest concentrations, absorbance, and conductivity occurred in Thomas Basin closest to the river inlets. Concentrations, absorbance, and conductivity diminished with increasing distance from Thomas Basin due to mixing and dilution in water occupying the main reservoir basin. Water in the main basin is a mixture of approximately equal parts of Quabbin and Wachusett derived water and, therefore, had lower values of these parameters than the river discharges. Thus, April samples collected at Basin South

(Station 3412) had intermediate parameter values and Basin North (Station 3417), located farthest downgradient from Thomas Basin, had the lowest parameter values (Table 5).

The horizontal gradients became pronounced in the spring of 2001 because of an exceptional amount of precipitation (8 inches in March) and snowmelt runoff. Mean monthly discharge rates of the Quinapoxet and Stillwater Rivers in April were the highest recorded since USGS gauging stations were established on the rivers in the mid-1990s. The high rates of discharge and correspondingly elevated rates of nutrient delivery caused the lateral gradients in the above parameters to develop and become manifest in the April sample results.

Once the Quabbin transfer was initiated on May 16th, the influence of the Quinapoxet and Stillwater Rivers was counteracted and the horizontal gradients rapidly dissipated. Also at this time, the onset of thermal stratification and increased biological activity in the water column caused nutrient distribution in the reservoir to revert to previously documented seasonal and vertical patterns that recur annually. These patterns include low epilimnetic concentrations in summer resulting from phytoplankton uptake and higher concentrations accumulating in the hypolimnion due to microbial decomposition of sedimenting organic matter (Section 4.1 above).

Another indication of the divergent influences of the Quabbin transfer and the Wachusett watershed on reservoir water quality is evident later in the year after a summer of sustained transfer. Samples collected in October and December of 2001 document a reversal of springtime horizontal gradients with the concentrations or intensities of certain parameters lowest in Thomas Basin and increasing downgradient. Although not as pronounced as the springtime gradients because of biological and stratification effects on nutrient distribution superimposed during the summer, this reversal of gradients demonstrates that Thomas Basin had been flushed out by the Quabbin transfer while receiving negligible inputs from the Quinapoxet or Stillwater Rivers. During the late summer period of annual minimum river flow and sustained transfer, Thomas Basin was essentially an extension of the Quabbin hypolimnion.

In summary, the relatively elevated concentrations observed in April 2001 reflect high discharge rates from the Quinapoxet and Stillwater Rivers operating prior to the entry of water transferred from Quabbin. Other than the springtime expansion in the ranges of nutrient concentrations in 2001 discussed above, the seasonal and vertical patterns in the distribution of nutrients from quarterly samples were comparable to those documented in the 1998-99 database (Section 4.1 above).

4.2.3 Influence of Robust Quabbin Transfer: Data from 2002

Consistent with patterns and trends in data documented since 1998-99, the Quabbin transfer was evident as the dominant influence on Wachusett Reservoir nutrient concentrations in 2002. Results of quarterly nutrient sampling in 2002 documented concentrations that generally registered at the low end of the historical ranges (see complete quarterly database in Appendix B). In particular, silica and UV absorbance were measured at concentrations and intensities below the minimum values observed previously (Table 6). The generally low nutrient concentrations recorded in 2002 are yet another expression of the linkage of Wachusett Reservoir to Quabbin Reservoir.

Table 6 - Comparison of Ranges of Silica and UV254 from 1998-01 Database(1) to Results from 2002 Quarterly Sampling (2)

Sampling Station (3)	Silica (SIO_2; mg/L)		UV254 (Absorbance/cm)	
	1998-01	Quarterly'02	2000-01	Quarterly'02
Basin North/3417 (E)	0.82 - 3.02	0.59 - 1.59	0.038 - 0.068	0.032 - 0.048
Basin North/3417 (M)	1.41 - 3.31	0.77 - 1.73	0.039 - 0.079	0.032 - 0.062
Basin North/3417 (H)	1.84 - 3.92	1.27 - 2.48	0.038 - 0.069	0.032 - 0.043
Basin South/3412 (E)	0.88 - 3.84	0.56 - 1.66	0.035 - 0.085	0.031 - 0.049
Basin South/3412 (M)	1.40 - 4.03	0.95 - 1.68	0.036 - 0.089	0.032 - 0.055
Basin South/3412 (H)	1.89 - 4.13	1.64 - 2.42	0.036 - 0.091	0.038 - 0.047
Thomas Basin (E)	1.13 - 5.00	0.62 - 4.23	0.026 - 0.136	0.028 - 0.140
Thomas Basin (M)	1.29 - 4.94	0.88 - 4.13	0.026 - 0.147	0.031 - 0.146
Thomas Basin (H)	1.26 - 4.99	0.92 - 4.18	0.027 - 0.150	0.028 - 0.131

Notes:

(1) 1998-01 database composed of 1998-99 year of monthly sampling and subsequent quarterly sampling through December 2001, except for measurement of UV254 initiated in 2000 quarterly sampling

(2) 2002 quarterly sampling conducted May, July, October, and December

(3) Water column locations are as follow: E = epilimnion/surface, M = metalimnion/middle, H = hypolimnion/bottom

The year 2002 was exceptional in that transfer occurred each and every month, albeit sporadically in the months of March, April, and May. Historically, the peak period of transfer from Quabbin consists of July, August, and September each year, with usually no transfers during February, March, or April. However, by April of 2002, the cumulative volume of water transferred from Quabbin amounted to a record high 64.4 million cubic meters, equivalent to 26 percent of the Wachusett basin volume. A sustained transfer was initiated on June 13th and continued through November 18th (except for a brief cessation of transfer during the last five days of September). By the end of October, the cumulative volume of water transferred from Quabbin amounted to a record high for that annual period of 208 million cubic meters or 83 percent of the Wachusett basin volume.

In a year such as 2002, with transfer occurring throughout the year and mostly continuously, nutrient concentrations will range lower due to the early entry and greater proportion of Quabbin derived water occupying the basin. At the conclusion of 2002, the transfer volume totaled 229 million cubic meters, equivalent to 91 percent of the Wachusett basin volume. Conversely, in years with delayed or reduced inputs from Quabbin or higher amounts of local precipitation or snowmelt, nutrient concentrations will range higher as discharges from the Quinapoxet and Stillwater Rivers have greater proportional influence (Sections 4.2.1 and 4.2.2 above).

The low silica concentrations measured in 2002 occurred mainly in July, especially in samples collected in the epilimnion and metalimnion. At this time of year, consistent with a seasonal pattern that recurs annually, uptake of silica by diatoms and their subsequent sedimentation causes the store of this nutrient to be depleted in upper portions of the water column. In 2002, this seasonal demand for silica was superimposed on concentrations already relatively low due to the robust transfer from Quabbin. The combination of these factors contributed to the minimum silica concentrations observed in 2002.

The low UV absorbance values measured in 2002 occurred mostly in October when the cumulative volume of water transferred from Quabbin amounted to a record high for that time of year (see above). This degree of dilution with Quabbin water with its much lower UV absorbance value (averaging 0.02 A/cm at the point of entry into the Quabbin Aqueduct), contributed to the minimum UV absorbance values observed in 2002 in Wachusett Reservoir.

Another indication of the divergent influences of the Quabbin transfer and the Wachusett watershed on reservoir water quality is evident in samples from Thomas Basin. At this location in 2002, the concentrations and intensities of most parameters are elevated in May and again in December (see complete quarterly database in Appendix B). The transfer from Quabbin was weakest at these times during 2002 resulting in the influence of the Quinapoxet and Stillwater Rivers becoming strongly evident in Thomas Basin which is the sampling location closest to the point of discharge of these rivers.

In summary, the relatively low concentrations observed in 2002 reflect the early entry and greater proportion of Quabbin derived water occupying the basin. Other than values at the low end of the ranges of nutrient concentrations and parameter intensities discussed above, the seasonal and vertical patterns in the distribution of nutrients in 2002 quarterly samples were comparable to those documented in the 1998-99 database (Section 4.1 above).

4.3 Results of Field Duplicate Analyses

As part of the nutrient sampling program, the reliability of laboratory results were checked by submitting duplicate samples of Wachusett Reservoir water as well as duplicates of samples collected from Quabbin Reservoir and Quabbin tributaries. Different locations were selected each month for collection of duplicate pairs of samples. Duplicates were collected simultaneously in the field using identical methods, containers, and preservation. One set of bottles of the duplicate pair was labeled only as field duplicate and, therefore, was a "blind" duplicate sent to the laboratory with no reference to location. All samples were stored together and delivered to the laboratory at the same time. A total of 33 duplicate samples were submitted to the laboratory over the 1998-99 year of study (generally three duplicate samples each month). Quarterly sampling since the conclusion of the monthly program (through December 2002) has generated data from an additional 24 duplicate samples.

Results of laboratory analysis of the field duplicates were evaluated using the coefficient of variation as a measure of laboratory precision (Table 7). Coefficient of variation (CV) is the standard deviation expressed as a percentage of the mean and was calculated for each analyte in each of the duplicate pairs of samples. Values around 20 percent indicate reasonable precision with lower values indicating good to excellent precision. Conversely, values greater than 20 percent indicate poor precision.

Table 7 - Summary of Coefficients of Variation (CV) Calculated for Duplicate Samples

Parameter	Median CV	Average CV	Maximum CV	Percent of CV values >20%
Total Phosphorus	11.4%	20.4%	120.3%	28.6%
Ammonia-Nitrogen	1.1%	5.9%	48.1%	10.5%
Nitrate-Nitrogen	0.9%	7.0%	133.0%	7.0%
Total Kjeldahl-Nitrogen	8.2%	14.8%	73.8%	28.6%
Silica	0.8%	1.5%	15.2%	none
Alkalinity	3.4%	7.2%	52.5%	12.1%
UV254 Absorbance (quarterly samples only)	1.0%	1.4%	4.9%	none

Results for silica exhibit the greatest precision with a median CV value of 0.8 percent, an average CV value of 1.5 percent, and no duplicate pairs having a CV greater than 20 percent. Measurements of silica were remarkable in their precision with concentrations in samples ranging from 579 to 13,900 ug/L and discrepancies between duplicate pairs generally 20 ug/L or less, especially in the lower range of values. Measurement of UV254 absorbance was initiated in 2000 quarterly sampling, including the collection of field duplicates, and has proved to be a highly precise measurement comparable to silica (Table 7). Nitrate was the next most precise laboratory measurement with a median CV value of 0.9 percent and only 7.0 percent of duplicate pairs having a CV greater than 20 percent.

Measurements of total phosphorus and total Kjeldahl-nitrogen were the least precise with median CV values of 11.4 and 8.2 percent respectively. These parameters also had the highest proportion of duplicate pairs with a CV greater than 20 percent (both with 28.6 percent). However, the concentrations of these parameters in the samples were often below or near the laboratory detection limit and this factor contributed to the difficulty of making precise measurements.

4.4 Evaluation of Historical Nutrient Data

The DWSP has contracted numerous consultant studies of Wachusett Reservoir over the years focusing on water quality models, nutrient and plankton dynamics, and other topics. Historical nutrient data from consultant studies are tabulated in Appendix C along with an annotated bibliography of all historical documents reviewed for this report.

4.4.1 Sources and Limitations of Historical Nutrient Data

Historical measurements of nutrients in Wachusett Reservoir are documented in the reports from two sampling programs conducted by private firms under contract with the DWSP. The consulting firm of Tighe & Bond conducted sampling and nutrient analysis of Wachusett Reservoir (and other DWSP resource waters) from May 1986 through May 1988 (Tighe & Bond, 1988). A shortcoming of this study is that sampling was limited to surface grabs (or epilimnetic composites), which precluded the detection of vertical variations in the concentrations of certain nutrients, a major feature of the recently generated database.

However, the DWSP 1988 annual report refers to data generated from samples collected at various depths by Tighe & Bond in 1987 and early 1988 that apparently were omitted in the report produced by Tighe & Bond in 1988. The DWSP 1988 annual report also documents nutrient data from a program of vertically stratified sampling conducted by DWSP staff from June through August with the samples sent to the Tighe & Bond laboratory for analysis. Some of the Tighe & Bond results reported by DWSP (1988 annual report) show seasonal and vertical patterns consistent with recent findings (see Section 4.4.2 below).

Approximately six years after Tighe & Bond concluded their sampling program the DWSP contracted the consulting firm of Camp, Dresser, & McKee (CDM) to expand the existing database and build on their previous studies (see Appendix C). They conducted sampling and nutrient analysis at Wachusett Reservoir from April 1994 through December 1994 (CDM, 1995). Sampling at various depths in the water column was a component of this study and CDM results show seasonal and vertical patterns consistent with recent findings (see Section 4.4.2 below).

Both studies entailed field measurements and water sampling at a variety of locations across the basin including some of the main sampling stations used in the present study such as Basin North/Station 3417, Basin South/Station 3412, and Thomas Basin. Many of the stations currently used for contemporary monitoring efforts are those originally established in these historical studies. Data from these historical reports are summarized in Appendix C.

During the period from 1990 through mid-1998, efforts were made to generate additional nutrient data through routine sampling conducted by DWSP staff. These samples were sent to one and then another private laboratory for analysis under contract with the DWSP. Unfortunately, scatter and inconsistencies are prevalent in the data reported by both these laboratories which have therefore been omitted from consideration in this report.

In comparison to recently generated nutrient data, the historical studies by Tighe & Bond (1988) and CDM (1995) suffer from the shortcomings of laboratory techniques then available, which did not have the sensitivity or reliability of analyses performed at the MWRA Deer Island Central Laboratory. In particular, minimum detection limits for ammonia and nitrate were much higher than the 5 ug/L detection limit of recent analyses (Table 8). In the case of the Tighe & Bond report, ammonia and nitrate are quantified in relatively broad increments of 10 ug/L as opposed to 1 ug/L increments documented in recent analyses. However, the low CDM detection limit for total phosphorus of 1 ug/L is a more exact measure of this parameter in comparison to recent analyses.

Table 8 - Comparison of Minimum Detection Limits in Historical Studies

Parameter*	Tighe & Bond (1988)	CDM (1995)
Ammonia-Nitrogen	• 10 ug/L • reported in 10 ug/L increments	• 10 ug/L
Nitrate-Nitrogen	• 40 ug/L • reported in 10 ug/L increments	• 30 ug/L
Total Phosphorus	• stated as 2 ug/L, but lowest reported value was 5 ug/L	• 1 ug/L
* detection limit in recent MWRA measurements of parameters listed above was 5 ug/L and results were reported in increments of 1 ug/L		

The CDM sampling program included collection of field duplicates that enable the reliability of laboratory results to be checked according to the coefficient of variation calculation used on recent data as described in Section 4.3 above. In comparison to recent MWRA measurements, CDM analyses of total phosphorus demonstrate similar precision and those of nitrate-nitrogen slightly less precision (Table 9). In contrast, recent measurements of ammonia-nitrogen are much more precise than those conducted by CDM.

Table 9 - Comparative Precision of Historical (CDM, 1995) and Recent MWRA Laboratory Measurements

Parameter	**Median CV**		**Average CV**		**Max. CV**		**Percent of CV values >20%**	
	CDM	MWRA	CDM	MWRA	CDM	MWRA	CDM	MWRA
Total Phosphorus	15.7%	11.4%	17.9%	20.4%	70.7%	120.3%	30.4%	28.6%
Nitrate Nitrogen	2.3%	0.9%	10.8%	7.0%	118.5%	133.0%	14.3%	7.0%
Ammonia Nitrogen	22.1%	1.1%	38.3%	5.9%	137.9%	48.1%	53.6%	10.5%
Chlorophyll A	47.1%	na	58.4%	na	118.3%	na	80.0%	na

The CDM report also includes data on chlorophyll-A, but it is evident in the very high CV values calculated for duplicate samples that measurements of this parameter are unreliable (Table 9). Due to inconsistencies in the chlorophyll data they have been omitted from consideration in this report.

4.4.2 Comparison of Historical to Recent Nutrient Data

Results reported by Tighe & Bond (1988) for total phosphorus and ammonia appear erroneous, being much higher than reported by CDM (1995) or the recent data. Nitrate data reported by Tighe & Bond also ranges high by comparison and appears insensitive to the pronounced pattern of nutrient depletion in the epilimnion resulting from seasonal phytoplankton activity as documented in recent data (Section 4.1.1 above). However, nitrate data reported by DWSP in the 1988 annual report for vertically stratified samples collected from June through August and analyzed at the Tighe & Bond laboratory reinforce recent findings. These data show seasonal depletion of nitrate in the epilimnion and accumulation in the hypolimnion.

The CDM ammonia data also ranges improbably high and are known to be inconsistent (based on duplicate samples; Table 9), but tend to show seasonal demand for this nutrient as documented in recent data. The CDM study documents total phosphorus concentrations generally in the range of 2 to 5 ug/L throughout the summer, thus reinforcing the finding of phosphorus as the limiting nutrient based on recent data. Additionally, the CDM data for nitrate demonstrates both seasonal demand by phytoplankton in the epilimnion (trophogenic zone) and accumulation of higher concentrations in the hypolimnion (tropholytic zone) as documented in recent data.

Both historical studies document the alternating influences of the Quabbin transfer and inputs from the Quinapoxet and Stillwater Rivers. The Tighe & Bond study provides only a hint of this interaction in data on color and turbidity from a sampling station located just downgradient of Thomas Basin east of the Route 12 Bridge (Station 3410). Values of color and turbidity in surface grabs are elevated in spring when watershed inputs are greatest, whereas lower values are recorded during the summer period of transfer from Quabbin.

Stronger evidence of this interaction is documented in the CDM (1995) data for Thomas Basin and Station 3410. Values of total phosphorus and nitrate-nitrogen are elevated in spring (April through June of 1994) forming a lateral gradient of decreasing concentrations downgradient similar to the pattern resulting from strong watershed influence documented in 2001 (Section 4.2.2 above). Once the Quabbin transfer was initiated in late June of 1994, the data show an immediate and substantial decrease in the concentrations of these parameters that persists for the remainder of the transfer period (through November of 1994).

Both historical studies report generally low, but temporally stable concentrations of alkalinity consistent with recent data. Plankton data in both historical studies also reinforce findings documented by recent data (see Section 5.0 below).

5.0 RESULTS OF PLANKTON ANALYSES

Most monitoring efforts have focused on phytoplankton rather than zooplankton due to the strong influence of phytoplankton productivity on water quality and the propensity of certain phytoplankton taxa to cause unpleasant taste and odors in water supplied to consumers. Results for phytoplankton and zooplankton are discussed separately in the sections that follow.

5.1 Phytoplankton

The main sources of recent phytoplankton data are the 1998-99 year of monthly sampling and the separate program of weekly sampling conducted off the catwalk at the rear of Cosgrove Intake since 1987 (see Section 2.2 above; important additional sources of data include two particularly comprehensive historical studies conducted by DWSP in 1988 and 1989 which are discussed in Section 5.3 below). Each of the sets of recent data have strengths and weaknesses.

The 1998-99 monthly data has the advantage of spatial coverage of the reservoir basin and provides insight into plankton dynamics in the reservoir at large. However, it is composed of a much smaller number of samples over only a single year and integrated tube sampling precluded the detection of vertical patterns in plankton growth associated with thermal stratification. This set of data is presented in Section 5.1.1 below.

Sampling of phytoplankton at Cosgrove has the advantage of easy accessibility in that it does not require a boat and it provides critical information on potential problems with “taste and odor” organisms at the point where water enters the distribution system. However, in terms of understanding plankton dynamics in the reservoir at large, this location has disadvantages.

Foremost among these is that seasonal patterns of plankton growth and succession occurring in the reservoir are suppressed or altered by periodic applications of copper sulfate adjacent to Cosgrove Intake to reduce populations of taste and odor organisms. Additionally, vertical patterns associated with thermal stratification such as the development of high population densities at discrete depths can become obscured in proximity to Cosgrove Intake. This is due to destabilization of stratification boundaries caused by the relatively shallow depth (16 meters) at this location, mixing induced by water flow over a submerged dike approaching the intake and at the point of withdrawal, and seiche effects caused by wind events.

Despite these shortcomings, the database spanning 16 years of weekly monitoring at Cosgrove underpins current understanding of plankton dynamics in Wachusett Reservoir. This data and the patterns they reveal are discussed in Section 5.1.2 below.

5.1.1 Monthly Reservoir Data from 1998-99

A total of approximately 40 phytoplankton taxa were observed in the quantitative samples collected during the year of study (see Appendix D for complete phytoplankton database). Most major groups of algae were represented among the Wachusett Reservoir phytoplankton including Chrysophyta (diatoms and other “golden-brown algae”), Cyanophyta (“blue-green algae” or cyanobacteria), and Chlorophyta (“green algae”). Total densities ranged from 36 to 1,440 ASUs/ml (excluding surface grabs collected during the initial sampling effort in October 1998) with seasonal variations in density and community composition generally consistent across all sampling stations except Thomas Basin.

Thomas Basin usually has lower densities than stations in the main basin, probably because of the higher flushing rate of this component of the reservoir system. The flushing rate of Thomas Basin becomes especially elevated during the spring period of peak runoff and when it is receiving water transferred from Quabbin. Lower densities in Thomas Basin compared to the main basin are also documented in historical data from 1996 (Section 5.3 below).

The sampling program was initiated near the end of one growing season (October 1998), continued through the winter period of minimal activity, and encompassed most of the next growing season. However, the results of the sampling program are discussed chronologically starting with the winter lull in phytoplankton activity through the beginning of a single growing season to its end. This approach is useful for describing phytoplankton dynamics and appropriate due to their regularity from year to year (see below).

The seasonal succession of phytoplankton in Wachusett Reservoir followed a pattern characteristic of many temperate, oligotrophic systems (Figure 7). During the winter period of low temperatures and light intensities growth by phytoplankton was sufficient only to maintain low population densities. Total densities in January 1999 ranged from 162 to 249 ASUs/ml and were composed mostly of diatoms and the cyanophyte *Microcystis*. Ice cover on the reservoir never formed completely during the winter of 1998-99. Samples collected in February and March were dominated by diatoms with total densities ranging from 231 to 638 ASUs/ml.

Phytoplankton growth was triggered in the spring as light conditions improved and water temperatures increased. Populations expanded rapidly during the period of spring mixis (late March through April) and reached a spring maximum dominated by diatoms in May at the onset of thermal stratification. Phytoplankton densities ranged from 455 to 1,360 ASUs/ml in the samples collected in May with diatoms composing an average of 78 percent of total densities across all sampling stations. The most abundant diatom of the spring maximum was *Asterionella* followed by *Cyclotella*, *Tabellaria*, and *Synedra*. Also contributing to the May maximum were the chrysophyte *Dinobryon* and the cyanophyte *Microcystis*.

The May maximum of phytoplankton populations depleted the supply of major nutrients in the trophogenic zone (Section 4.1 above) resulting in subsequent population declines as growth was offset by losses due to sedimentation. Phytoplankton densities in June ranged from 36 to 659 ASUs/ml. In addition to declines in density following the May maximum, the composition of the phytoplankton community shifted to dominance by the cyanophyte *Microcystis* instead of diatoms. Diatoms were observed only infrequently through the summer, fall, and early winter.

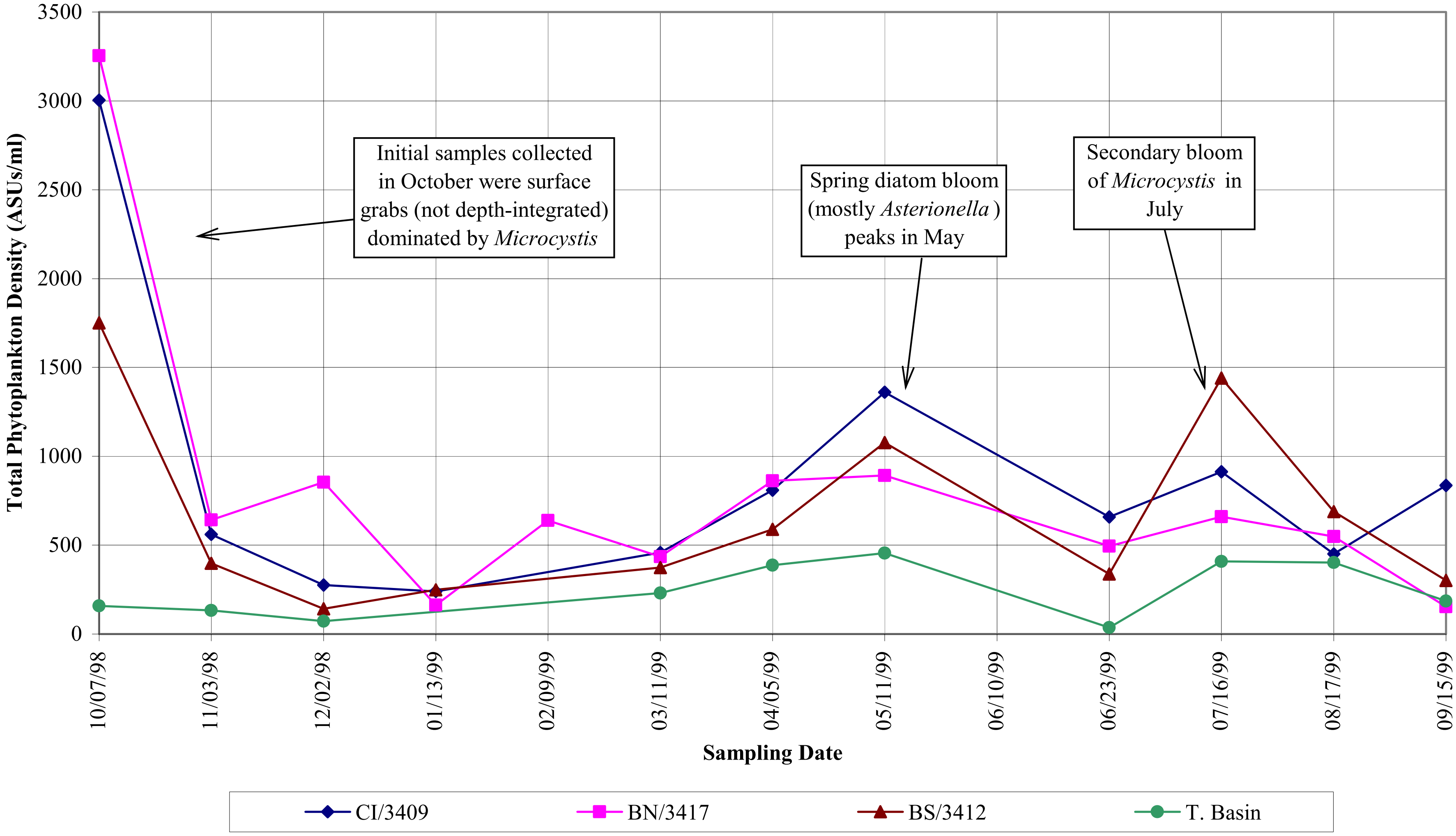
Populations of *Microcyst*is rebounded in July, especially at Basin South (Station 3412) where densities reached 1,440 ASUs/ml. In August, densities of *Microcystis* declined at all stations. Another cyanophyte, *Aphanocapsa*, became codominant with *Microcystis* in August and persisted on into September. In September, populations generally declined with densities ranging from 154 to 302 ASUs/ml except at Cosgrove Intake where growth by *Aphanocapsa* contributed to a total density of 836 ASUs/ml.

As stated previously, initial plankton sampling in October 1988 consisted of grab instead of depth-integrated samples and these data are anomalous compared to the results generated subsequently. The very high densities recorded at this time (around 3,000 ASUs/ml at Cosgrove Intake and Basin North) are partly an artifact of this technique given that *Microcystis*, the dominant organism in these samples, may accumulate near the surface. However, reduced Secchi transparency (Figure 8, see below) suggest that, despite the difference in sampling technique, the high densities recorded in October indicate an actual peak in phytoplankton growth. The weekly sampling at Cosgrove Intake performed at this time records low phytoplankton densities and the contradiction between data sets is likely due to differences between analysts in how the amorphous colonies of *Microcystis* were identified and enumerated microscopically.

Densities at all stations declined between the October and November sampling dates and, except for Basin North (Station 3417), continued to decline through December. Populations of *Microcystis* and diatoms at Basin North are responsible for a minor peak of growth in December (855 total ASUs/ml). Densities at all other stations in December ranged from 73 to 276 ASUs/ml. The general pattern of a fall maximum in phytoplankton densities, such as observed in October 1998, followed by population declines coinciding with the onset of low winter light intensities and water temperatures is characteristic of temperate, oligotrophic systems.

Measurements of Secchi transparency in 1998-99 are generally consistent with the pattern of phytoplankton dynamics described above (Figure 8). Relatively low transparency values were observed in March, April, and May ranging from 5.5 to 5.8 meters (18 to 19 feet). The diminished transparency of the water in the spring coincides with the period of growth by phytoplankton leading to peak densities observed in May. In winter and summer, when densities of phytoplankton were low, Secchi transparencies were greater ranging from 6.7 to 8.5 meters (22 to 28 feet). The maximum phytoplankton densities observed in October 1988 surface grabs coincided with the minimum transparency observed during the year of study measured at 5.2 meters (17 feet).

Figure 7 - 1998-99 Phytoplankton Monitoring: Summary of Seasonal Abundance Patterns



Initial samples collected in October were surface grabs (not depth-integrated) dominated by *Microcystis*

Spring diatom bloom (mostly *Asterionella*) peaks in May

Secondary bloom of *Microcystis* in July

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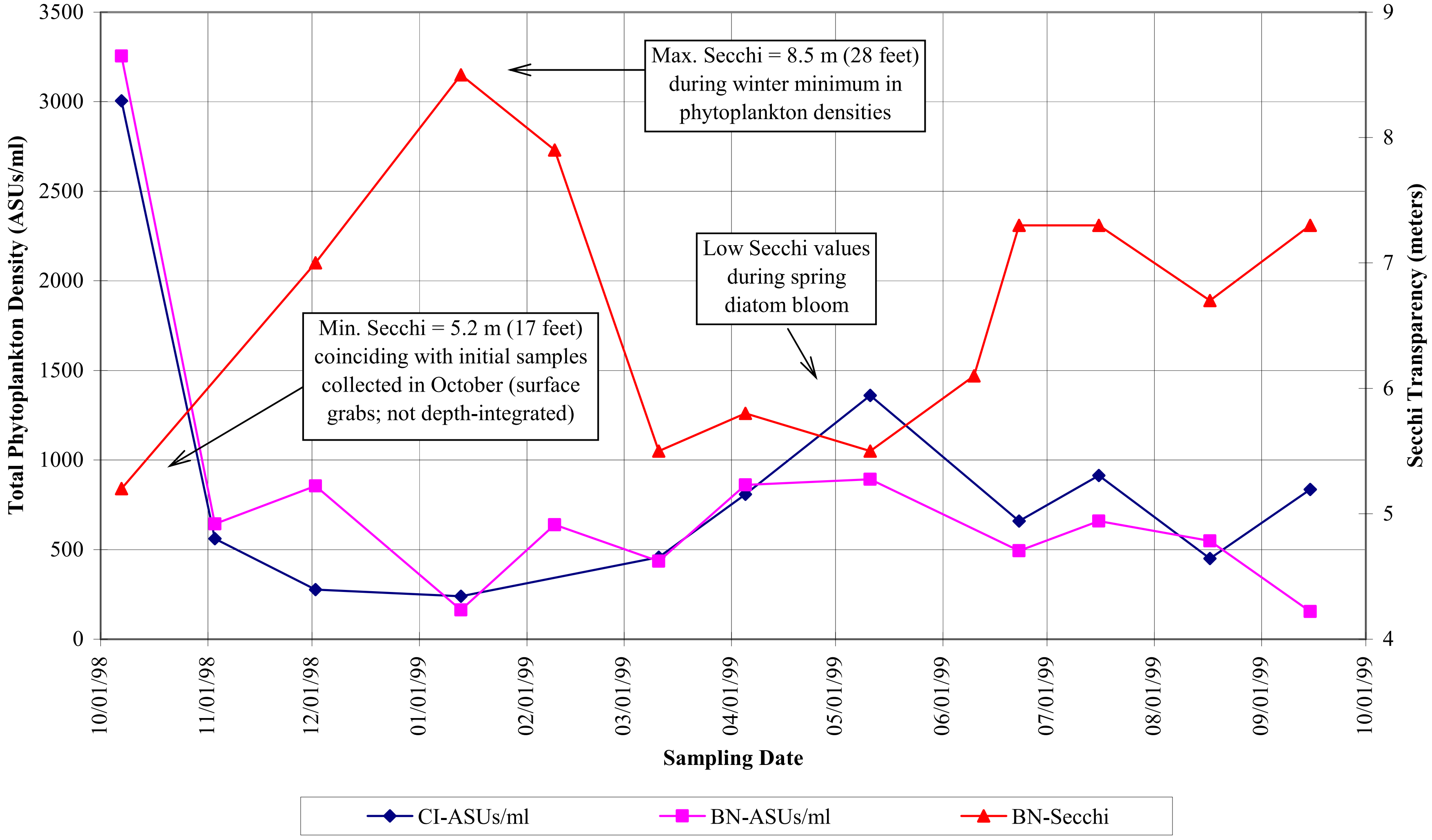
Figure 8 - 1998-99 Phytoplankton Monitoring: Relationship of Density to Secchi Transparency



Max. Secchi = 8.5 m (28 feet) during winter minimum in phytoplankton densities

Low Secchi values during spring diatom bloom

Min. Secchi = 5.2 m (17 feet) coinciding with initial samples collected in October (surface grabs; not depth-integrated)

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5.1.2 Weekly Cosgrove Intake Data from 1987 to 2002

Phytoplankton populations monitored at Cosgrove Intake generally follow the seasonal pattern outlined in Section 5.1.1 above, but additional details are revealed in the Cosgrove database which is reviewed here. Small populations of diatoms characterize a winter lull in phytoplankton activity from January through March due to low light availability and low temperatures. Total densities during these early months are generally less than 300 ASUs/ml, but a few years have had densities ranging up to 800 ASUs/ml. As light intensity increases and water temperatures rise there is a period of rapid growth with a spring maximum in May composed mostly of diatoms at all depths. *Asterionella* usually comprises 50% to 90% of organisms observed at this time, but *Rhizosolenia* and assorted centric diatoms are sometimes co-dominant.

Densities during the spring diatom bloom generally approach 900 to 1,000 ASUs/ml and a few years have had spring densities reaching 1,200 to 1,700 ASUs/ml. This spring diatom bloom is usually followed by a rapid decline in densities as the water column becomes thermally stratified. Diatom densities remain very low during the summer and fall, and then increase again during the late fall and early winter as water temperatures decrease.

Following the spring peak in diatom densities and thermal stratification of the water column, the cyanophyte genera *Anabaena* and *Microcystis* become dominant in June. There is generally a minor peak of chrysophytes dominated by *Uroglenopsis*, *Dinobryon*, *Synura*, or *Chrysosphaerella* also around this time. Seasonal succession patterns among phytoplankton populations in the vicinity of Cosgrove Intake are often altered in June and/or July by copper sulfate applied at the surface to reduce populations of *Anabaena*, *Synura*, or other taxa that cause unpleasant taste and odors in water supplied to consumers.

The magnitude of the spring diatom bloom appears to predispose the reservoir ecosystem to one of two alternative successional patterns involving *Synura*, a critical taste and odor genus. In years when peak densities associated with the spring diatom bloom remained below 1,000 ASUs/ml, *Synura* densities have always increased to problematic levels (greater than 20 ASUs/ml) in June or later during the early fall. Conversely, in years when late winter and early spring diatom densities are higher (usually more than 500 ASUs/ml) and maximum bloom densities exceed 1,000 ASUs/ml, *Synura* densities remain below the concern threshold of 20 ASUs/ml throughout the year.

Summary data for the past eight years (Table 10) shows that *Synura* has exceeded the level of concern five times. In each of those five years, diatom densities during the first five months did not exceed 1,000 ASUs/ml. During the three years (1997, 1998, and 2000) when *Synura* densities never exceeded the concern threshold, spring densities of diatoms were greater than 1,000 ASUs/ml.

Table 10 - Inverse Relationship of Spring Diatom Bloom to *Synura* Growth

Year	Maximum Diatom Densities in Spring	*Synura* Densities Relative to Threshold of 20 ASUs/ml
1995	950 ASUs/ml	Exceed (236 ASUs/ml)
1996	750 ASUs/ml	Exceed (110 ASUs/ml)
1997	1,700 ASUs/ml	Under
1998	1,240 ASUs/ml	Under
1999	985 ASUs/ml	Exceed (28 ASUs/ml)
2000	1,500 ASUs/ml	Under
2001	600 ASUs/ml	Exceed (21 ASUs/ml)
2002	900 ASUs/ml	Exceed (29 ASUs/ml)

Both diatoms and *Synura* require silica to make their unique cellular structures. The inverse relationship between maximum spring diatom densities and subsequent growth of *Synura* is likely due to depletion of this nutrient by robust diatom growth and subsequent sedimentation (see Section 4.1.2 above). Replenishment of silica to the water column after a vigorous diatom bloom in spring apparently does not occur in time to support significant growth of *Synura* populations later in the year.

The filamentous cyanophyte *Anabaena* has caused taste and odor problems historically each year in June, but the MWRA has established a policy of treating the area adjacent to Cosgrove Intake with copper sulfate as soon as *Anabaena* densities begin to increase, and this prompt action generally eliminates the annual bloom. Over the past five years densities of *Anabaena* have not exceeded 60 ASUs/ml and no complaints have been registered recently.

Over this same recent period, however, a trend of increasing densities of total cyanophytes has been noted. Cyanophytes have been observed each summer over the past fourteen years, but densities generally have been low, with the exception of the annual *Anabaena* bloom. Total cyanophyte densities (excluding the short bloom period for *Anabaena*) never exceeded 100 ASUs/ml prior to 1999, with summer densities generally between 50 and 80 ASUs/ml. In contrast, total cyanophyte densities exceeded 150 ASUs/ml in 1999 and again in 2000, and exceeded 300 ASUs/ml in 2001. The colonial cyanophyte *Microcystis,* previously rare to uncommon at Wachusett, has been the most commonly observed genus during the summer and fall of recent years. This organism was also a dominant component of the phytoplankton community observed in the 1998-99 year of monthly reservoir sampling (Section 5.1.1 above). On the other hand, this apparent trend of ascension by cyanophytes did not continue in 2002 with maximum cyanophyte densities reaching only a modest 100 ASUs/ml.

Chrysophytes usually remain at low densities until mid-May each year. A bloom of chrysophytes may occur as early as mid-May or as late as July, with densities increasing from near 50 ASUs/ml to as high as 900 ASUs/ml. *Dinobryon* is almost always present; *Chrysosphaerella* and *Uroglenopsis* are also commonly observed. A second bloom of chrysophytes often follows later in the summer between August and October. The

MWRA usually applies copper sulfate in the vicinity of Cosgrove Intake to control these blooms or a concurrent bloom of *Anabaena*. However, peak population growth of chrysophyte genera often occurs at or near the boundary between epilimnion and metalimnion (at depths of around 6 to 8 meters), so these surface algaecide treatments are not always successful in reducing chrysophyte densities.

As explained above, *Synura* densities appear to be inversely linked with spring diatom densities. This troublesome genus is generally present at very low densities during much of the year, often increasing in the water column at the end of May and during June, but declining following the annual copper sulfate treatment for *Anabaena*. Densities usually increase again during August during years with low springtime diatom densities, especially at depth, and are sometimes very difficult to suppress even with multiple surface applications of copper sulfate.

Chlorophytes are generally present throughout the year, but are usually only a minor component of the phytoplankton community with total chlorophyte densities almost never reaching 100 ASUs/ml. Highest densities are usually observed from June through September. Chlorophytes may comprise up to 50% of total phytoplankton densities in the early fall, with less representation during the remainder of the year.

5.2 Zooplankton

A total of 13 zooplankton taxa were observed in the qualitative samples collected with a plankton net during the 1988-99 year of study. The zooplankton community of Wachusett Reservoir was composed of the typical freshwater fauna of rotifers (Rotatoria) and two groups of microcrustacea; Cladocera (cladocerans or water fleas) and Copepoda (copepods). Populations of rotifers were generally dominant throughout the year and were represented by the following seven genera: *Keratella*, *Kellicottia*, *Asplanchna*, *Polyarthra*, *Gastropus*, *Brachionus*, and *Conochilus*. Four species of cladocera were observed consisting of *Bosmina longirostris*, *Daphnia catawba*, *Daphnia dubia*, and *Holopedium gibberum*. Copepod populations consisted of representatives of the two planktonic suborders Calanoida and Cyclopoida. These results from the 1998-99 year of study represent a preliminary investigation into the zooplankton community of Wachusett Reservoir and more detailed work is planned for the future.

5.3 Comparison of Historical to Recent Plankton Data

In addition to the monthly reservoir data from 1998-99 (Section 5.1.1) and the weekly Cosgrove data from 1987 to 2002 (Section 5.1.2), plankton data was generated in six separate historical monitoring programs consisting of the two consultant studies discussed previously in regard to historical nutrient data (Section 4.4 above) and programs conducted by DWSP in 1988, 1989, 1995, and 1996. These programs included plankton sampling at locations in the main basin and at multiple depths (except the Tighe & Bond study was restricted to epilimnetic samples). Data from these programs provide insight into plankton dynamics in the reservoir at large and vertically in the water column without the limitations of data from the 1998-99 depth-integrated sampling or sampling at Cosgrove Intake. In particular, programs conducted by the DWSP in 1988 and 1989 entailed frequent sampling at three stations in the main reservoir basin, each at multiple depths, and comprise the most comprehensive record of spatial plankton patterns in the reservoir so far assembled.

A final source of historical plankton data is that compiled by the Massachusetts Water Resources Authority (MWRA) from 1987 through 1999. This database contains analysis results for samples collected at numerous locations in the MWRA distribution system serving Greater Boston as well as Wachusett Reservoir. Most data about the reservoir come from samples collected off the catwalk at the rear of Cosgrove Intake (similar to, but independent from those collected by DWSP), but a few data originate from sampling locations in the main basin and at multiple depths (see annotated bibliography in Appendix C for a brief summary of MWRA findings).

Plankton data generated from the two historical consultant studies (Tighe & Bond, 1988 and CDM, 1995) are summarized with the nutrient data given in Appendix C. Plankton data from historical monitoring programs conducted by DWSP in 1988, 1989, 1995, and 1996 are given in the annual reports for those years (see Appendix C for a compilation of historical Secchi transparency measurements recorded by DWSP). The scope and findings of these six historical plankton monitoring programs are described below.

Tighe & Bond, 1988 (sampling conducted in 1986-88, report published in 1988)

- This sampling program was conducted May 1986 through March 1988 and was discussed previously in regard to historical nutrient data (Section 4.4 above). Most sampling was focused on Station 3409 (Cosgrove), but the database also includes results from sampling at Station 3410 and sporadic sampling at Stations 3412 and 3417. It entailed the use of a 80 micron mesh plankton net manipulated vertically to a depth of 10 feet. A total of 31 net samples were collected over the course of this study with phytoplankton densities reported as ASUs/ml (and number/ml) and zooplankton densities reported as number/L. The main features of this data are spring diatom blooms (1986 and 1987) as well as high diatom densities in December and March of 1988 when ice cover was lacking. Data on Secchi transparency accompany the plankton data, but are contradictory and appear unreliable (highly doubtful measurements of 0.8 and 1.3 feet were recorded at Cosgrove Intake and Station 3410 respectively on October 20, 1987). Measurements of chlorophyll-A concentrations were measured at a third location (Station 3412), but these show no correlation with plankton or Secchi data generated at the other stations.

  In addition to diatoms, the Tighe & Bond study identified *Dinobryon* as a consistent component of the phytoplankton community and often contributing to peaks in densities. Among the zooplankton, the rotifers *Kellicottia* and *Conochilus* were identified as the dominant organisms which is consistent with the recent finding of dominance by these and other rotifers. This study also reported occasional observations of the cladocerans *Leptodora* and *Polyphemus* in the net samples. These two organisms were not observed during the 1998-99 year of study or in subsequent quarterly sampling and it is likely that the Tighe & Bond analyst misidentified one or the other and/or confused one with *Holopedium gibberum*. In particular, *Polyphemus* is an unlikely inhabitant of the reservoir limnetic zone being generally restricted to pools, marshes, and littoral zone habitats.

DWSP, 1988 (sampling conducted in 1988, results published in annual report)

- The database from this sampling program and the following year (1989, see below) provide a detailed record of spatial plankton patterns in the reservoir. The 1988 data consists of a total of 195 samples collected from March through November at three reservoir locations (Stations 3410, 3412, and 3417) with each station sampled at multiple depths. This sampling program documents a diatom bloom early in the year throughout the mixed water column and an epilimnetic resurgence in June (maximum in June of 741 ASUs/ml). Once the water column became thermally stratified between May 4th and 26th, densities observed in the hypolimnion (at depths of 15 and 21 meters at Station 3412 and 18 and 27 meters at Station 3417) were consistently lower than in the epilimnion, usually much lower. The low hypolimnetic densities were composed mainly of diatoms, likely senescent and in the process of sinking to the bottom. In the epilimnion, minimum densities were recorded from July through October, except for episodic peaks in populations of the chrysophytes *Chrysosphaerella* and, secondarily, *Synura* near the boundary between epilimnion and metalimnion in August (maximum of 313 ASUs/ml). A secondary diatom bloom was observed in November and encompassed the entire water column as fall turnover had occurred and the water column was in a state of mixis. Secchi transparency was recorded on ten dates during this program and the expected inverse correlation with measurements of phytoplankton density is evident (Figure 9).

DWSP, 1989 (sampling conducted in 1989, results published in annual report)

- The database from this sampling program and the previous year (1988, see above) provide a detailed record of spatial plankton patterns in the reservoir. The 1989 data consists of a total of 135 samples collected from April through November at three reservoir locations (Stations 3410, 3412, and 3417) with each station sampled at three depths (surface, mid-depth, and deep). It documents a spring (April through early-June) diatom bloom throughout the water column (maximum of 954 ASUs/ml), a bloom of *Anabaena* at the surface on June 19th (maximum of 163 ASUs/ml), and episodic peaks in populations of the chrysophyte *Uroglenopsis* occurring at Station 3412 on June 19th and August 7th and at Station 3417 on June 5th and on October 10th through 24th. Generally these chrysophyte peaks were positioned within the epilimnion and were of modest densities except for June 5th at Station 3417 when densities reached 340 ASUs/ml. A minor resurgence in diatom densities within the epilimnion was observed in early September. Minimum densities were recorded in July and again in late September through November. Secchi transparency was recorded on sixteen dates during this program and, similar to 1988, transparency measurements are inversely correlated with phytoplankton density (Figure 10). The all-time records for both minimum and maximum Secchi transparency in Wachusett Reservoir were recorded in 1989 with the minimum of 2.2 meters (7.2 feet) observed at Station 3412 on June 19th and the maximum of 8.8 meters (29 feet) observed at this same station on October 10th.

Camp, Dresser, and McKee, 1995 (CDM; sampling conducted in 1994, report published in 1995)

- Sampling and analysis of plankton was performed by DWSP staff in coordination with CDM as part of a broader sampling program (discussed in regard to historical nutrient data in Section 4.4 above). A total of 13 samples were collected from April through December 1994 at Station 3412, these being a combination of composite samples (surface to 2 meters; total of eight) and grab samples collected at various depths (8, 10, and 18 meters; total of five). Main features of the data generated at Station 3412 are the lack of a pronounced diatom bloom in spring (maximum of 170 ASUs/ml), the appearance of *Anabaena* in surface waters later in the year (late summer and fall) rather than in June, episodic peaks in populations of chrysophytes (*Uroglenopsis* in the epilimnion in June and *Dinobryon* at a depth of 8 meters in August), and highest diatom densities in November (maximum of 487 ASUs/ml). Secchi transparency was recorded on nine dates during this program, but no clear relationship to phytoplankton densities is apparent due to the irregularity of sampling and small number of samples.

DWSP, 1995 (sampling conducted in 1995, results published in annual report)

- This program was conducted April through November 1995 and consisted of vertically stratified sampling at Station 3412 (surface and 8 or 10 meters; total of 16 samples). Main features of the data generated at Station 3412 are a spring (April - May) diatom bloom (maximum of 940 ASUs/ml), the absence of a significant June *Anabaena* bloom, and a bloom of *Dinobryon* (125 - 158 ASUs/ml) persisting at a depth of 8 meters from July 12th through September 20th. A secondary peak in diatom densities was observed in November. Secchi transparency was recorded on four dates during this program.

Figure 9 - 1988 Phytoplankton Monitoring: Seasonal Abundance and Secchi Transparency

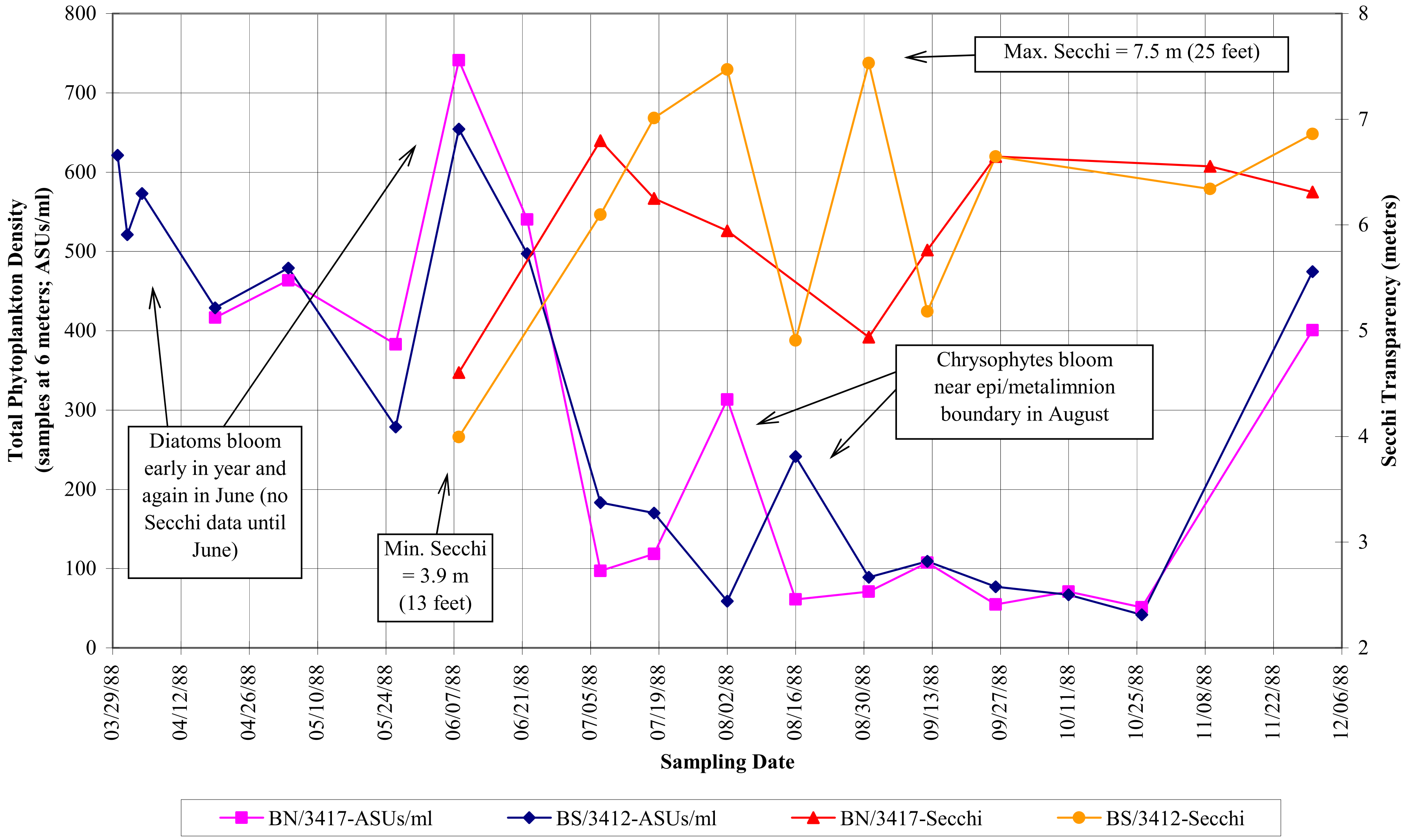

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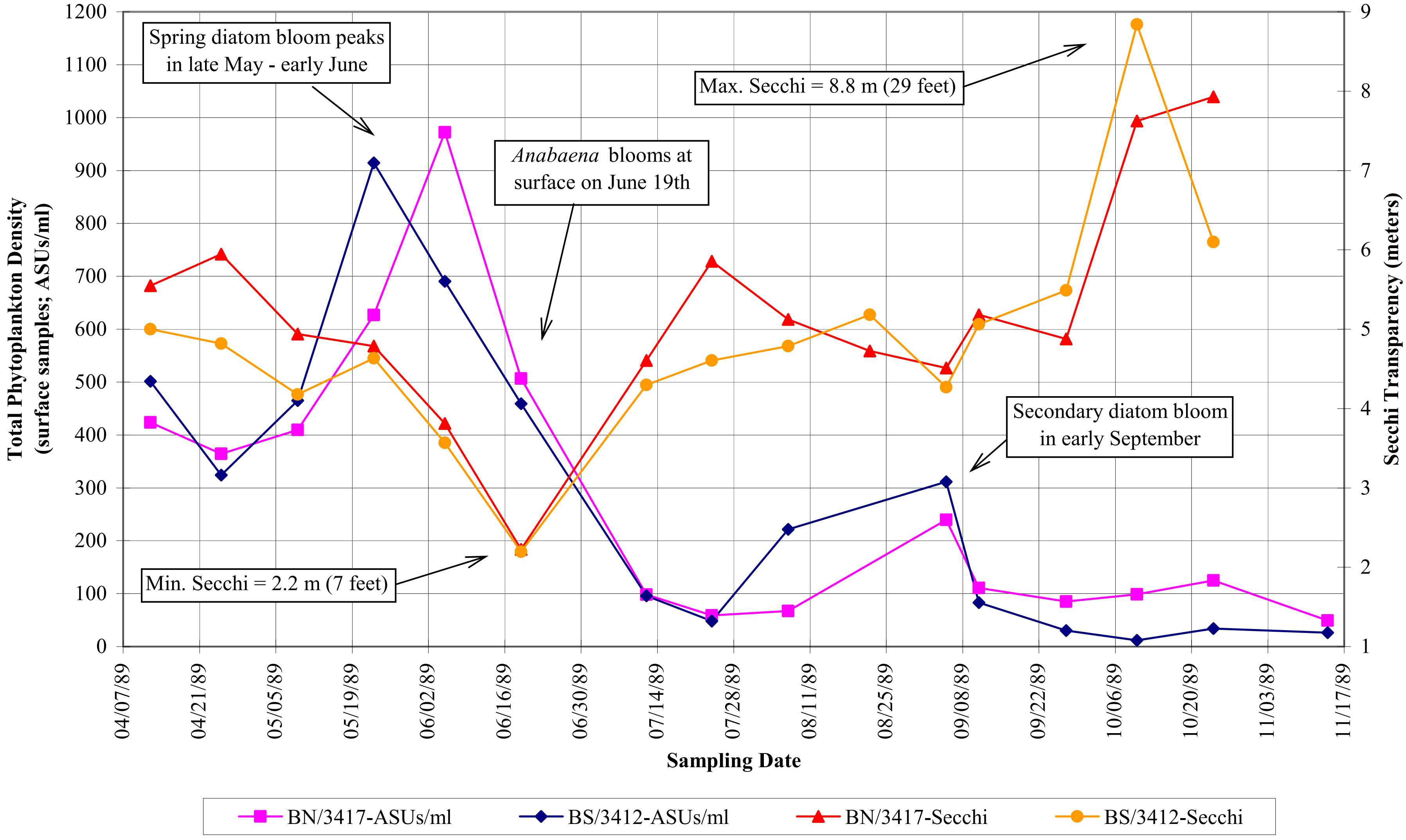
Figure 10 - 1989 Phytoplankton Monitoring: Seasonal Abundance and Secchi Transparency



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DWSP, 1996 (sampling conducted in 1996, results published in annual report)

- This program was conducted April through November 1996 and consisted of vertically stratified sampling at Station 3412 (surface, 8 meters, and 20 meters) and Thomas Basin (surface and 6 meters; total of 40 samples). Main features of the data generated at these stations are a spring (April - May) diatom bloom (maximum of 583 ASUs/ml), simultaneous blooms of *Uroglenopsis* and *Anabaena* on June 10th (maximum densities of 1,179 and 73 ASUs/ml respectively), and a second, even greater diatom bloom in November (maximum of 722 ASUs/ml). Minimum densities were recorded from July through September. Densities in Thomas Basin were much lower than at Station 3412 on most sampling dates, except for hypolimnetic samples (20 meters) at Station 3412 which had the lowest densities (15 - 18 ASUs/ml) from July through September. Secchi transparency was not recorded during this program.

5.4 Synopsis of Annual Phytoplankton Succession in Wachusett Reservoir

Wachusett Reservoir supports a phytoplankton community dominated by diatoms and chrysophytes with lesser densities of cyanophytes, chlorophytes, and dinoflagellates; a community typical of many oligotrophic, softwater systems located in the temperate zone. This assemblage of phytoplankton taxa exhibits an annual cycle of succession in the reservoir that is also fairly typical of this type of system. Basic features of this cycle consist of the following: minimal activity in winter due to low light intensities and low temperatures, a spring maximum dominated by diatoms, a summer minimum following the spring depletion of nutrients, a secondary peak in the fall, and then a return to low winter densities.

Based on the review of historical and contemporary data in the foregoing sections, additional details of this cycle and features unique to the phytoplankton of Wachusett Reservoir can be identified (Table 11). The generalized pattern depicted in Table 11 is subject to variability within any given year. For example, even a major feature in the pattern such as the spring diatom bloom is occasionally delayed, as in 1990 when they did not peak until July, or is nearly absent as in 1994.

Chrysophytes including *Dinobryon*, *Chrysosphaerella*, *Uroglenopsis*, and *Synura* exhibit the greatest spatial and temporal variability among all major groups of phytoplankton. All of these genera consist of motile (flagellated) colonies which can adjust, to a limited degree, their vertical position in the water column. These organisms are likely among those responsible for spikes in dissolved oxygen concentrations observed at or near the interface between epilimnion and metalimnion (a "positive heterograde curve") typical of many temperate lakes and reservoirs (Wetzel, 1983). This narrow stratum of elevated dissolved oxygen concentration results from photosynthetic activity where organisms have aggregated at a certain depth in the water column. The thermal boundary between epilimnion and metalimnion is accentuated in Wachusett Reservoir due to the Quabbin interflow and the sharp gradient may provide chrysophytes and/or other organisms with the optimal combination of temperature, light, and nutrient availability. More detailed investigations of this phenomenon are planned for the future.

The convergence of environmental factors contributing to optimal conditions for growth is generally seasonal for major groups of phytoplankton and probably achieved only briefly for specific taxa in most ecosystems. In Wachusett Reservoir, small-scale variations or gradients in temperature, light, and nutrient availability apparently coincide favorably to produce episodes of rapid growth among chrysophytes. These variations in environmental factors occur both spatially and temporally depending mostly on local weather patterns and stratification characteristics of the water column. Localized blooms of chrysophytes stimulated by favorable, but transitory combinations of environmental factors take place in the broader context of seasonal and long-term influences. Most important in terms of long-term nutrient loading and availability is the annual interaction between the divergent influences of the Quabbin transfer and the Wachusett watershed.

Table 11 - Generalized Annual Cycle of Phytoplankton Community Dynamics in Wachusett Reservoir

TIME OF YEAR AND WATER COLUMN CHARACTERISTICS	**Jan. - April**	**May**	**June**	**July - Aug.**	**Sep. - Oct.**	**Nov. - Dec.**
	• Water column mixing prior to and after ice-out	• Development of thermal stratification pattern: epilimnion, metalimnion, and hypolimnion	• Water column thermally stratified • Quabbin transfer generally penetrating main basin as interflow around this time	• Water column thermally stratified • Metalimnetic interflow stratum established throughout main basin	• Epilimnion cools and thermal stratification weakens • Epilimnion is eventually mixed with interflow stratum followed shortly by fall turnover (complete mixing)	• Water column mixing until ice cover forms
PHYTOPLANKTON COMMUNITY DYNAMICS	• Diatom populations grow rapidly ("bloom") after ice-out (predominantly *Asterionella*, often followed by *Rhizosolenia*)	• Diatom populations peak and then decline (or decline after peaking earlier in spring; max. densities usually approach 1,000 ASUs/ml, but can go higher)	• *Anabaena* blooms at the surface (applications of copper sulfate usually initiated around Cosgrove Intake) • Blooms of chrysophytes also occur commonly in the epilimnion or at the epi/metalimnion boundary at this time	• Most populations subside (low to moderate densities of cyanophytes and chlorophytes persist; max. densities usually less than 300 ASUs/ml)	• Secondary blooms and declines of chrysophytes, cyanophytes, and/or diatoms frequently occur	• Diatoms grow moderately; populations of other taxa generally remain at low densities

NOTES ON IMPORTANT PHYTOPLANKTON TAXA:

1.) Diatoms bloom in spring and again, usually secondarily, in fall/winter (favor lower temperatures); bloom densities generally span the entire water column due to their coinciding with intervals of mixing at the beginning and end of the stratification period; however, diatom blooms occurring in late summer/fall are restricted to the epilimnion and top of the metalimnion in a stratified water column (low densities are reported in the hypolimnion in the 1988, 1989, and 1996 databases; these are likely specimens sedimenting from upper strata and undergoing senescence; other taxa are rarely observed in the few hypolimnetic samples composing the historical database).

2.) *Anabaena* populations are generally restricted to surficial waters and typically undergo a short-lived (weeks) bloom in June, but can appear at significant densities later in the year or skip a year and reappear the following year.

3.) Chrysophytes exhibit the most spatial and temporal variability among all taxa; they can peak asynchronously across basin and/or at different depths (generally from the surface to a depth of 9 meters); blooms of *Synura* appear to be inversely correlated to the relative intensity of the annual spring diatom bloom (see Section 5.1.2 above).

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6.0 SUMMARY AND CONCLUSIONS

- Results confirm "oligotrophic" status (Wetzel, 1983) of Wachusett Reservoir based on low concentrations of total phosphorus and total inorganic nitrogen (this status is dependent on the Quabbin transfer functioning as the major hydrologic input); as an oligotrophic system Wachusett Reservoir provides high quality drinking water to consumers.

- Concentrations of all nutrients and patterns of season fluctuation were similar across all sampling stations in the main basin of the reservoir (except for hypolimnetic values at Cosgrove Intake where mixing with the interflow obscures trends evident elsewhere); temporary horizontal gradients can become pronounced for certain parameters depending on the prevailing balance between the Quabbin transfer and watershed inputs (see below).

- Concentrations of ammonia, nitrate, and silica exhibited marked seasonal and vertical variations due to demand by phytoplankton in the trophogenic zone (epilimnion and upper metalimnion) and decomposition of sedimenting phytoplankton in the tropholytic zone (lower metalimnion and hypolimnion).

- Ammonia and nitrate were depleted in the trophogenic zone in April and July respectively and remained below or near the detection limit of 5 ug/L through September, whereas concentrations of these nutrients increased in the tropholytic zone (ammonia increased in the hypolimnion from May through August and nitrate from May through fall turnover).

- Minimum concentrations of silica were measured in the trophogenic zone in July through September, whereas hypolimnetic concentrations increased from May through fall turnover.

- Concentrations of total phosphorus were low throughout the year at all stations and depths with levels generally ranging from 5 to 10 ug/L; this indicates that phosphorus is the limiting nutrient for Wachusett Reservoir phytoplankton.

- The Quabbin interflow generally forms between depths of 6 and 15 meters in the water column and its presence is conspicuous as a metalimnetic stratum of low conductivity and also in the relatively low concentration ranges of nutrients in the metalimnion, especially nitrate, silica, and alkalinity.

- During periods of water column isothermy and mixing (late fall and early winter before ice and early spring after ice), the water column was homogenized (no vertical gradients) with concentrations of most nutrients intermediate between summer extremes measured in the trophogenic and tropholytic zones.

- In Thomas Basin, concentrations and intensities of all parameters vary widely depending on the interplay between the Quabbin transfer and the Wachusett watershed; during extended summer periods of transfer Thomas Basin is flushed out and essentially becomes an extension of the Quabbin hypolimnion with low nutrient concentrations, but at times when discharges from the Quinapoxet and Stillwater Rivers are the predominant loading sources (especially in spring before transfer initiation) nutrient concentrations shift to higher ranges.

- Interannual fluctuations in nutrient concentrations and parameter intensities occur throughout the main basin as a result of the divergent influences of the Quabbin transfer and the Wachusett watershed; temporary lateral gradients across the basin can become pronounced for nitrate, silica, UV254, and conductivity either increasing or decreasing downgradient of Thomas Basin depending on the dominant influence.

- The zooplankton community of Wachusett Reservoir is composed of the typical freshwater fauna of rotifers (Rotatoria) and two groups of microcrustacea; Cladocera (cladocerans or water fleas) and Copepoda (copepods). Rotifers present the most diversity among Wachusett zooplankton and their populations are generally dominant throughout the year.

- Wachusett Reservoir supports a phytoplankton community typical of many oligotrophic, softwater systems located in the temperate zone with diatoms and chrysophytes dominant, accompanied by lesser densities of cyanophytes, chlorophytes, and dinoflagellates.

- Wachusett Reservoir exhibits an annual cycle of phytoplankton succession characteristic of many temperate, oligotrophic systems consisting of the following: minimal activity in winter due to low temperatures and light intensities, a spring maximum dominated by diatoms, a summer minimum following the spring depletion of nutrients, a secondary peak in the fall, and then a return to low winter densities.

- Chrysophytes exhibit the most spatial and temporal variability among all phytoplankton taxa; they can peak asynchronously across basin and/or at different depths (generally from the surface to a depth of 9 meters); multiple years of data from Cosgrove Intake suggest that blooms of the problematic taste and odor genus *Synura* are inversely correlated to the relative intensity of the annual spring diatom bloom.

- Current and historical measurements of Secchi transparency are consistent with the seasonal periodicity of phytoplankton described above with greatest clarity documented during summer periods of low densities and periods of reduced transparency corresponding to spring and fall maximums.

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