RELATIONSHIPS BETWEEN LARGEMOUTH BASS MERCURY LEVELS AND ENVIRONMENTAL CHARACTERISTICS OF CONNECTICUT LAKES

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EXECUTIVE SUMMARY

In 1995-1996, the Environmental Research Institute of the University of Connecticut conducted a study entitled "Preliminary assessment of total mercury concentrations in fishes from Connecticut water bodies." The University of Connecticut's Department of Natural Resources Management and Engineering and the Institute of Water Resources were partners in this project. The study was conducted in cooperation with the Connecticut Department of Environmental Protection (DEP) and the Connecticut Department of Public Health (DPH). Results of this study are presented in two reports. The first report (Neumann et al. 1996), focused on the first phase of the study and provided data summaries for fish and sediment mercury concentrations from numerous water bodies throughout Connecticut. The second report (presented herein) focuses on the second phase of the study and provides information on environmental characteristics of lakes related to mercury concentrations in largemouth bass *Micropterus salmoides*. This report utilizes fish mercury data, water quality data, and lake physical attribute data obtained during 1995-96 (phase 1). Values for individual fish mercury concentrations can be found in Neumann et al. (1996); environmental attributes of lakes are included in this report.

The concentrations of mercury in fish have been shown to be related to a variety of environmental characteristics of aquatic systems, both chemical and physical. Fish from waters with low acid-neutralizing capacity often contain elevated levels of methylmercury in axial muscle tissue; the greater accumulation of methylmercury in low pH waters has been attributed to greater in lake microbial production of methylmercury. Physical lake characteristics such as watershed area/lake volume ratio and other morphometric features have been directly correlated with mercury in fish. Identification of these relationships in Connecticut lakes may be useful for assessing the role of the environment on mercury concentrations in fish. Identification of environmental attributes of lakes related to mercury levels in fish may help identify sites where mercury levels in fish may be potentially high. Moreover, understanding the linkages between fish mercury levels and the environment will help assess potential changes in fish mercury levels associated with environmental change.

The objectives of this study were: 1) to determine the relationship between mercury concentrations in largemouth bass and environmental characteristics (both chemical and physical) of Connecticut lakes; and 2) to examine environmental characteristics of lakes on a regional scale that may help understand observed regional differences in largemouth bass mercury concentrations.

Mercury concentrations in axial muscle tissue of 478 largemouth bass representing 51 lakes and five ecoregions were determined. In some instances, measurements for particular environmental variables were not obtained for specific lakes. Therefore, some relationships presented herein are based on less than 51 lakes (no less than 58). Relationships were based on expected levels of mercury for a fourteen-inch largemouth bass from each lake to remove the confounding effects of body size and to make comparisons among water bodies meaningful. Significant negative correlations were found between largemouth bass mercury concentrations and conductivity, pH, alkalinity, Ca, Mg, dissolved organic carbon, particulate phosphorus, and morphoedaphic index (an indicator of lake productivity). Redox potential

was the only variable significantly positively related to mercury concentrations. The variables most strongly correlated to mercury levels in largemouth bass were those related to water acidity (pH and alkalinity) and hardness (conductivity, Ca, and Mg).

Multiple regression procedures were used to determine the relationships between largemouth bass mercury concentrations and combinations of environmental variables. Using combinations of physical variables only, morphoedaphic index and lake surface area accounted for 25% of the variation in largemouth bass mercury concentrations among lakes. Using combinations of chemical variables only, Ca and dissolved organic carbon accounted for 31% or the variation in mercury concentrations among lakes. Using combinations of physical and chemical variables, Ca, dissolved organic carbon, watershed area, surface area, and maximum depth accounted for 53% of the variation in mercury concentrations among lakes. Over twice the variability in mercury concentrations among lakes was explained using combinations of variables than when only one environmental variable was used (e.g., conductivity, Ca, Mg, pH, or alkalinity). However, in multiple regression models, Ca was the dominant variable explaining mercury concentrations. Therefore, measures of acidity and hardness appeared to be the primary variables related to largemouth bass mercury levels in Connecticut lakes, although other variables may help explain additional factors influencing mercury concentrations.

The inverse relationships between mercury concentrations and variables associated with acidity and hardness are consistent with findings of several similar investigations in other regions of North America. Results of this study also suggest that mercury levels in largemouth bass might be influenced by mercury loading from large watershed areas that drain into small water surfaces. Other researchers have speculated that humic substances may act as a source of mercury for methylating bacteria and that these humic materials might mobilize mercury from the watershed and act as a source of methylmercury to aquatic systems. Results of this study also suggest that mercury levels in largemouth bass may be related to lake productivity. Based on the multiple regression model, mercury levels in largemouth bass were positively influenced by lake maximum depth. In our study lakes, lake maximum depth was inversely related to measures of lake productivity such as morphoedaphic index and total dissolved phosphorus. Bioaccumulation of mercury in fish may be elevated in less productive lakes because mercury may become concentrated in the small amount of biomass produced annually in those systems. However, data presented herein suggest that morphometric and productivity variables may be secondary to other variables representing acidity and hardness, which appear to be the lead indicators of largemouth bass mercury levels in Connecticut lakes.

Five additional lakes, independent of our study lakes, were used to test whether the independent variable models that we found to be significant, accurately predicted mercury levels in largemouth bass. The correlation between predicted mercury concentration and the actual mercury concentration was strongest using conductivity. Although multiple variable models explained more variation in largemouth bass mercury concentrations than did single variable models based on the large set of lakes used in this study, conductivity alone accurately predicted mercury concentrations. These results provide preliminary evidence that measures of acidity and water hardness may be the primary factors influencing largemouth bass mercury concentrations in Connecticut lakes.

The ecoregion delineations used in this study appeared to be valuable for detecting regional differences in largemouth bass mercury concentrations within the state, and for identifying environmental characteristics on a regional scale that may be contributing to variability of mercury concentrations among regions. Ecoregion variations in bedrock geology, especially those related to acid-neutralizing capacity and hardness of waters, may be the primary reasons for the observed ecoregion variations in largemouth bass mercury concentrations. Largemouth bass mercury concentrations were generally higher in the southeastern region of the state, followed by the northeast, northwest, southwest, and central lowlands. Our lake samples showed that pH, alkalinity, conductivity, Ca, and Mg varied among ecoregions based on bedrock geology; this information helped explain regional differences in mercury concentrations.
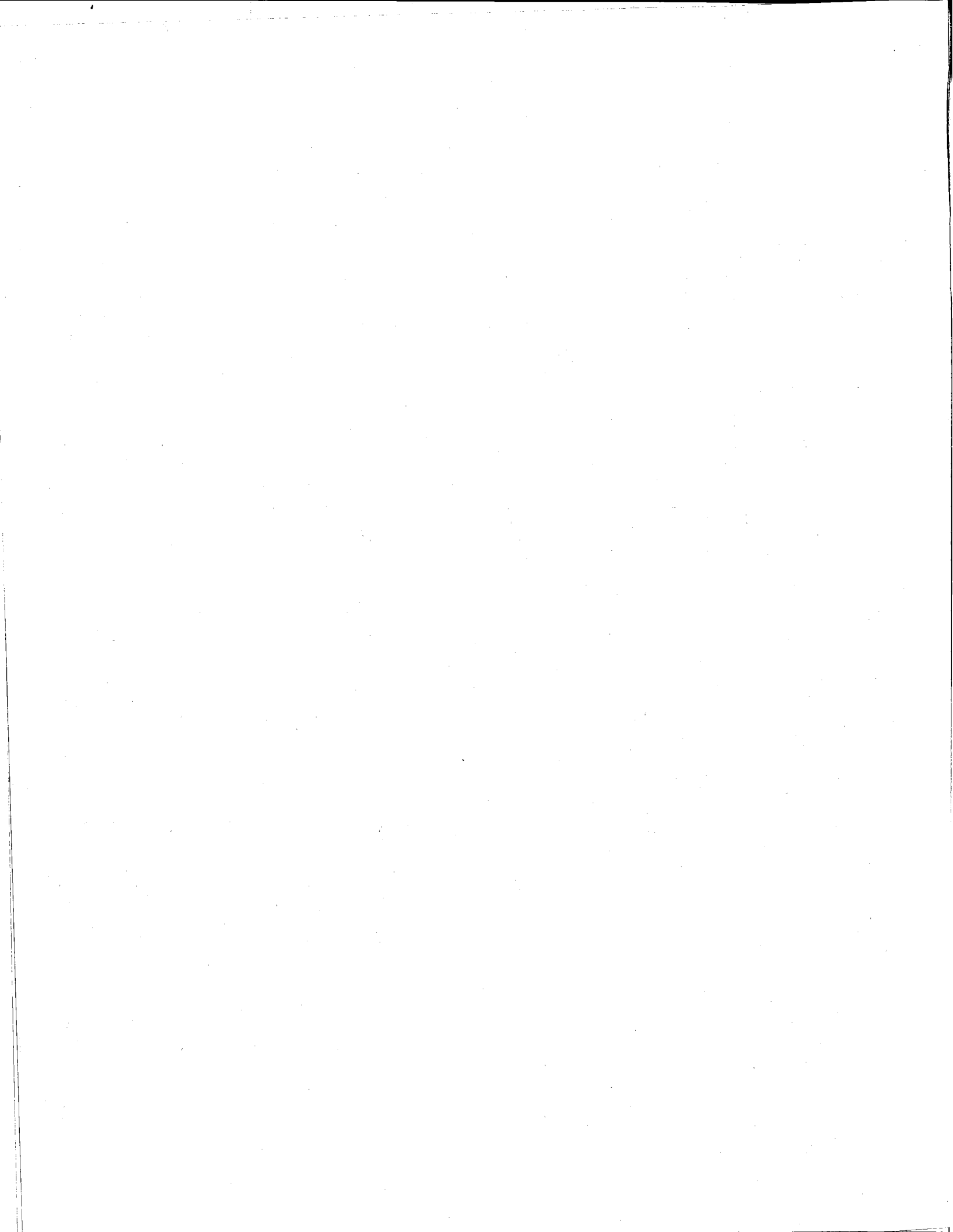
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INTRODUCTION

Mercury contamination in aquatic environments has been widely studied throughout North America and Europe. Where high concentrations of mercury exist, bioaccumulation of mercury in fish may pose health concerns for humans and fish-eating wildlife. Mercury contamination has been related to both natural and anthropogenic point and non-point sources. Atmospheric transport and deposition appear to be the primary vectors of mercury to aquatic systems (Mierle 1990; Fitzgerald and Clarkson 1991). Atmospheric mercury emissions from anthropogenic sources include combustion of fossil fuels (Nriagu and Pacyna 1988), incineration of municipal waste and sewage sludge (Nriagu and Pacyna 1988; Glass et al. 1990), and mining and metallurgy (EPA 1980; Nriagu and Pacyna 1988). Elemental mercury possesses long distance transport capabilities; therefore, sources may be local within the Southern New England region or distant including the Midwest industrial region (Fitzgerald and Clarkson 1991). While many historic point sources of mercury have been curtailed, contaminated sediments at these locations may continue to act as mercury sources (Suns and Hitchin 1990).

Atmospheric and point-source mercury enters aquatic ecosystems primarily in the elemental (inorganic) form (Driscoll et al. 1994). Mercury methylation occurs predominantly at the microbial level with the transformation of elemental mercury into its more toxic methylated form (i.e. methylmercury) (Rudd et al. 1983; Wiener et al. 1990). Methylmercury is environmentally different from the inorganic form in that it is more toxic, more mobile, and more readily bioaccumulated by aquatic organisms. Methylmercury is of greater health concern than inorganic forms due to its greater solubility in lipid tissue and thus, its increased tendency to bioconcentrate (Weber 1993). Human exposure to methylmercury compounds is almost exclusively from the consumption of fish and fish products. Consequently, elevated mercury levels in fish are of concern because of the direct health threat to humans, especially given the increased popularity of fish for dietary and health reasons. Methylmercury accounts for 95-99% of the total mercury found in the muscle tissue of freshwater fish (Grieb et al. 1990; Bloom 1992).

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Fish accumulate methylmercury primarily from their diet (Wiener et al. 1990; Lange et al. 1993; Futter 1994), and to a lesser extent, from water by direct uptake across the gill membranes (Phillips and Buhler 1978; Rodgers and Beamish 1983). For example, MacCrimmon et al. (1983) observed a sevenfold increase in the mercury content of stocked lake trout *Salvelinus namaycush* after a change in diet from benthic invertebrates to rainbow smelt *Osmerus mordax*.

Mercury concentrations in fishes have been directly related to fish age (MacCrimmon et al. 1983; Lange et al 1993), fish length (MacCrimmon et al. 1983; Lange et al. 1993; Futter 1994), and fish weight (Lange et al. 1993; Futter 1994). Futter (1994) noted a positive correlation between fish length and mercury concentration, and that length-adjusted mercury values are generally accepted in most studies where mercury concentrations in fish are being compared among systems. However, there was a considerable amount of unexplained variation for fish size and fish mercury concentration relationships; variability may be related to sex and age of fish. Lange et al. (1993) noted that in Florida lakes, male largemouth bass *Micropterus salmoides* greater than 200 mm had higher concentrations of mercury than females of the same size because the males were older. In addition to age, growth rate may be an important factor directly related to mercury accumulation in fish.

The concentrations of mercury in fish have been shown to be related to a variety of environmental characteristics of aquatic systems, both chemical and physical. Fish from waters with low acid-neutralizing capacity often contain elevated levels of methylmercury in axial muscle tissue; the greater accumulation of methylmercury in low pH waters has been attributed to greater in lake microbial production of methylmercury (Wiener and Spry 1996). Mercury levels in axial muscle tissue have been shown to be directly correlated to lake pH in pumpkinseed sunfish *Lepomis gibbosus* (Wren and MacCrimmon 1983), walleye *Stizostedian vitreum* (Wiener et al. 1990), and largemouth bass (Lange et al. 1993), and also with alkalinity in northern pike *Esox lucius* (Wren et al. 1991) and largemouth bass (Lange et al. 1993). Similar inverse relationships between mercury in muscle tissue and measures of water hardness (Ca, specific conductivity, and Mg) have been observed (Rodgers and Beamish 1983; McMurtry et al. 1989; Wren et al. 1991). Physical lake characteristics such as watershed

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area/lake volume ratio (McMurtry et al. 1989) and impoundment age (Bodaly et al. 1984) have been directly correlated with mercury in fish. Identification of these relationships in Connecticut lakes may be useful for assessing the role of the environment on mercury concentrations in fish. Identification of environmental attributes of lakes directly associated with mercury in fish may help identify sites where mercury levels in fish may be potentially high. Moreover, understanding the linkages between fish mercury levels and the environment will help assess potential changes in fish mercury levels associated with environmental change.

During a preliminary assessment of mercury levels in Connecticut fishes, Neumann et al. (1996) observed a significant inverse relationship between mercury levels in largemouth bass and lake pH. In addition, significant regional variations in largemouth bass mercury levels and pH of waterbodies were found. The objectives of the current study were to perform a more in-depth analysis of: 1) the relationships between mercury concentrations in largemouth bass and physical and chemical characteristics of Connecticut lakes; and 2) the regional patterns in environmental characteristics of lakes that may explain regional variations in mercury concentrations in fish. This report builds upon fish mercury and water quality data obtained during a previous survey (Neumann et al. 1996).

METHODOLOGY AND PROCEDURES

Study Sites

The base list of lakes from which the study lakes were chosen met the following criteria: 1) lakes that were greater than 10 ha; 2) lakes that were publicly owned or allowed public access; and 3) lakes that had a boat launch or were accessible with a portable boat. The base list of lakes also included those representing combinations of trophic classifications and alkalinity levels, based on a Connecticut Department of Environmental Protection (CTDEP) review of CTDEP data for approximately 100 lakes with public access. The concept of "ecoregions" was applied to aide in the selection and distribution of lakes for this study. Dowhan and Craig (1976) adopted the concept of ecoregions on the national scale, and developed ecoregions specific to Connecticut. These ecoregions have similar interrelationships among physiography, geography, local climate, soil profiles, and plant and animal

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communities. Thus, ecoregions are natural divisions of land, climate, and biota that are especially useful in forestry, wildlife management, land planning, and natural-resource monitoring management. Dowhan and Craig (1976) recommended that the degree of regional subdivision should depend on its usefulness to the researcher for purposes of scientific description. Thus, this study focused on five specific regions adapted from Dowhan and Craig (1976): northeast hills/uplands; southeast hills/coastal; northwest hills/uplands; southwest hills/uplands; and, central lowlands. In this study, examination of fish mercury levels on an ecoregion level may provide information on those attributes that are ecoregion-specific that may contribute to mercury concentrations in fish. The number and percentage of lakes sampled within each ecoregion that met the initial selection criteria were: northeast, 8 (28%); southeast, 14 (33%); central lowlands, 9 (56%); northwest, 9 (32%); and southwest, 11 (79%). By selecting a group of lakes within each ecoregion we were confident that our study lakes represented a wide range of environmental characteristics of lakes in Connecticut.

Largemouth bass were collected during bass angler tournaments and by boat electrofishing. Through the assistance of the Fisheries Division of the CTDEP, lakes with scheduled bass fishing tournaments were identified within each region. Electrofishing was conducted at locations within regions that were underrepresented by bass fishing tournaments (primarily the central lowlands and southwest). Thus, locations sampled within each region were not selected at random, but were selected based on the potential for fish collection through bass fishing tournaments or electrofishing where tournaments were not held. Therefore, the locations sampled probably provide a subset of the most popular bass angling sites.

Fish Collection

We attempted to collect at least ten largemouth bass from each lake distributed among the following length ranges: 300 - 379 mm, 380 - 457 mm, and >457 mm. Immediately upon collection, fish were stored in a clean polyethylene holding tank filled with ambient-lake water. To avoid contamination of fish by outboard motor exhaust plumes from boat electrofishing, the motor was shut off before processing fish and the person operating the

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motor was not allowed to assist in any fish processing. After fish collection, individual fish were removed from the tank, rinsed in ambient lake water and measured to the nearest millimeter total length (TL) on a clean, polyethylene-lined measuring board. The fish was then sealed in a polyethylene bag, weighed to the nearest g on tared dial-spring scale, double-bagged, placed in a clean cooler on dry ice, and returned to the laboratory at the Environmental Research Institute (ERI) at the University of Connecticut for subsequent analysis. Detailed fish collection and sample preparation protocol can be found in Neumann et al. (1996).

Laboratory Methods

The total time from fish capture to chemical analysis was no longer than 28 days, following standard EPA (1993) procedures. Frozen samples were thawed before necropsy. All fish were dissected in a positive-pressure laminar flow hood on acid-washed surfaces. Stainless steel instruments used for dissection were thoroughly cleaned before dissection of each fish. Scales were removed below the lateral line behind the anterior edge of the pelvic fin for subsequent age determination. The fish was placed with its left side facing up, a series of three cuts was made, and the skin was removed to expose the muscle tissue.

Individual fillets were homogenized in a stainless steel grinder and analyzed for total mercury. A 1.0-1.5-g subsample of homogenate was placed in an acid-washed biological oxygen demand (BOD) bottle and stored at -20°C until digestion. Eight ml of concentrated sulfuric acid and 2 ml of concentrated nitric acid were added, and the sample was placed on a 60°C hot plate until the tissue was completely dissolved (up to 1 hr). The BOD bottles were then removed from the hot plate and cooled to 4°C in a refrigerator. Ten ml of potassium permanganate were added, with an additional 10-20 ml of permanganate added until oxidizing conditions were maintained. Ten ml of potassium persulfate were added and samples were allowed to stand overnight. Excess potassium permanganate was reduced by the addition of hydroxylamine hydrochloride. All mercury in the samples (now in the form of Hg^{II}) was reduced by adding tin chloride to convert Hg^{II} to Hg^0. Total mercury was determined by flameless cold vapor atomic absorption spectroscopy.

A five-point calibration curve was run at the beginning of each analysis. The calibration curve was verified with a certified external quality control sample (initial calibration verification; ICV) from either the Ricca Chemical Company (Arlington, Texas) or Environmental Resource Associates (Arvada, Colorado). The initial calibration check demonstrated that the instrument was capable of acceptable performance at the beginning of the analysis. An initial calibration blank (ICB) was also run. The blank was made from the reagents used in the procedure, and matched the reagent matrix of the samples. In order to ensure continuing acceptable performance, a calibration verification and calibration blank were run at least every tenth sample. For every twenty samples, a procedural spiked-fish sample, duplicate fish samples, a control spike, and a preparation blank were analyzed. Precision of analysis (relative percent difference) was calculated from duplicate analyses of fish (mean, 5.7%; SD, 5.1; $N=36$). Accuracy (percent recovery) was determined from spiked fish samples (mean, 93.7%; SD, 6.4; $N=36$). The minimum detection limit was 0.03 μg Hg/g.

Determination of Chemical and Physical Lake Attributes

From each lake, water samples were collected using a Kemmerer bottle and additional water quality attributes were measured using a Hydrolab multiprobe. Samples and measurements were taken at the approximate center of each lake 1 m below the surface during summer and fall 1995. The Hydrolab multiprobe was used to measure and record pH, specific conductivity (COND), total dissolved solids (TDS), salinity, and redox potential. Water samples collected with the Kemmerer bottle were stored in precleaned 1-L bottles and placed in a clean cooler on dry ice. These samples were returned to the laboratory at ERI for determination of alkalinity, Mg, Ca, particulate carbon, organic carbon (total and dissolved), ammonia, particulate nitrogen, nitrate plus nitrite, nitrogen (total dissolved), phosphorus (dissolved inorganic), particulate phosphorus, phosphorus (total dissolved), and total suspended solids. All analyses and holding times were in accordance with standard Environmental Protection Agency (EPA) methods (as described in Neumann et al. 1996). Morphoedaphic index (MEI) was calculated as TDS divided by mean depth (Ryder 1965). Morphoedaphic index is commonly used as an estimate of potential fish yield (i.e., an

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indicator of lake productivity) (Carline 1986).

Physical lake attributes were measured during this study (Secchi depth) and obtained from CTDEP (1982, 1987, and 1991), Heally and Kulp (1995), Thomas et al. (1967), Thomas et al. (1968), Ryder et al. (1970), Wilson et al. (1974), Weiss et al. (1982), and Handman et al. (1986) and the geographic information systems (GIS) database through assistance of staff at the Natural Resource Center of the CTDEP. Physical characteristics of lakes included in the analysis consisted of volume, retention time, maximum depth, mean depth, Secchi depth, watershed area, surface area, perimeter, watershed area/lake area ratio, watershed area/lake volume ratio, shoreline development index, elevation, and MEI.

Data Analyses

Distributions of all variables used in statistical analyses were tested for normality by inspection of normal probability plots (UNIVARIATE procedure; SAS Institute 1990). Plots were performed for all variables using raw values and $\log_{10}$, $\log_{10}+1$, inverse, and square-root transformations. Variables were transformed when the linearity of the probability plot was improved after the transformation.

Linear regression (REG procedure; SAS Institute 1990) was used to test the relation of $\log_{10}$mercury concentration in largemouth bass to $\log_{10}$length, $\log_{10}$weight, and $\log_{10}$age for each population. The basis for these analyses was to determine which variable (length, weight, or age) was most highly and consistently correlated with mercury concentrations in largemouth bass across lakes, so standardized concentrations of mercury in fish could be determined for each lake in order to make meaningful comparisons among lakes. Mercury concentration was significantly related to length in more populations than either weight or age and correlation coefficients were higher for length; therefore, an expected mercury concentration (EHg) for largemouth bass was predicted for a total length of 356 mm based on the length-mercury regression from each lake and was rounded down to the nearest whole inch (14 inches =356 mm) for simplicity. A largemouth bass TL of 356 mm was near the grand mean (364 mm) for all fish sampled during this study. For lakes where no significant relationships between length and mercury were found, nonadjusted mercury values were used

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in subsequent analyses (Bodaly et al. 1993). Futter (1994) noted a positive correlation between fish length and mercury concentration, and that length-adjusted mercury values are generally accepted in most mercury studies.

Linear regression was used to test the relationships between EHg and each individual environmental variable. The relationships between EHg and combinations of chemical and physical variables of lakes were evaluated using stepwise multiple regression (REG procedure; SAS Institute 1990). Expected largemouth bass mercury concentrations for each lake were regressed against sets of the independent environmental variables. The environmental variables considered were first analyzed with chemical and physical variables separately, then with chemical and physical variables combined. Subsets of these environmental variables were created to remove the effect of multicollinearity among independent variables. Independent variables were included only if the regression coefficients were significant ($P \leq 0.05$), and multicollinearity did not exist among independent variables.

Analysis of variance (GLM Procedure; SAS Institute 1990) was used to test for regional differences in EHg and chemical and physical variables. When significant regional differences were found ($P \leq 0.05$), the Fishers Least Significant Difference (LSD) test was used to determine which regions were different.

Preliminary Tests of Predictive Utility

Largemouth bass were sampled from six additional lakes during 1996 to independently test the utility of several environmental variable models for predicting EHg. However, only five lakes were used in this analysis. One lake was not included because EHg of largemouth bass in that lake may be biased due to historic mercury contamination in that system. It must be made clear, however, that preliminary tests for predictive utility may not be valid for models containing few test cases. Multiple variable model testing requires a large sample size of independent test cases (a minimum requirement of five test cases per independent variable; Tabachnick and Fidell 1989). Therefore, tests for preliminary predictive utility conducted herein were only applied to single independent-variable models.

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RESULTS

Mercury concentrations in axial muscle tissue of 478 individual largemouth bass representing 51 lakes and five geographic regions ranged from 0.03 - 2.65 μg/g (wet weight) with a mean mercury concentration of 0.51 μg/g (wet weight). Mean fish length and weight for the entire sample were 364 (range=247 - 512) mm and 741 (range=196 - 2410) g, respectively. Mercury concentrations greater than or equal to 0.50 μg/g (wet weight) were found in 195 (41%) of the 478 largemouth bass analyzed. These fish represented 39 of the 51 (76%), lakes sampled.

A significant ($P<0.05$) positive correlation was found between EHg and redox potential (Table 1). Significant ($P<0.05$) negative correlations were found between EHg and specific conductivity (COND), pH, Ca, Mg, alkalinity, dissolved organic carbon (DOC), particulate phosphorus, and MEI. The chemical variable most strongly correlated with EHg was COND ($r=-0.51$, $P=0.0002$). Morphoedaphic index was the only physical variable significantly correlated with EHg ($r=-0.42$, $P=0.003$) based on individual variable regressions. The relationship between mercury concentration and MEI appeared to be strongest at MEI values less than 20. Examples of these correlations are shown in Figure 1. Parameter estimates of the relations between EHg and environmental variables are listed in Table 1.

Using combinations of physical variables, a significant ($P<0.05$) two-variable stepwise regression with MEI and surface area (SA) as independent variables accounted for 25% of the variation in EHg ($R^2=0.25$; $P<0.05$), yielding the following equation:

$$E\text{Hg}= 0.210 - 0.288(\text{MEI}) - 0.129(\text{SA}).$$

All other regression equations produced lower R^2 values.

A high degree of collinearity was found between pH, Ca, Mg, COND, and alkalinity (Table 2). Therefore, these variables were entered separately in regression subsets. Using only chemical variables, stepwise multiple regression revealed that two independent variables Ca and DOC accounted for 31% of the variation in EHg ($R^2=0.31$; $P<0.05$), yielding the

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following equation:

$$EHg = 1.208 - 0.523(Ca) + 0.414(DOC).$$

Dissolved organic carbon was significant only in variable subsets containing Ca. All other subsets produced one variable models (e.g., pH or COND) with lower R^2 values (see Table 1 for individual regression statistics). Although both Ca and DOC provided significant contribution to the model, Ca was the dominant variable explaining EHg based on partial r^2 values for each variable (Table 3).

Stepwise multiple regression of the chemical variables combined with physical variables revealed that Ca, DOC, watershed area (WA), SA, and maximum depth (MXD) accounted for 53% of the variation in EHg ($R^2 = 0.53$; $P < 0.05$), yielding the following equation:

$$EHg = 1.938 - 0.794(Ca) + 0.737(DOC) + 0.073(WA) - 0.266(SA) + 0.251(MXD).$$

Again, although DOC, WA, SA, and MXD were significant variables in the model, Ca was the dominant variable explaining EHg (Table 3). All other variable subsets produced one-variable models (e.g., pH or COND) with lower R^2 values.

Significant differences in largemouth bass EHg were found among ecoregions within the state ($P < 0.01$; Table 4). Mean EHg in the southeast region was significantly higher than the central lowlands, southwest, and northwest regions but not significantly different from the northeast region. No significant differences in lake MXD, lake WA, and lake SA were found among geographic regions in the state. However, significant differences in mean MEI were found among geographic regions ($P < 0.0001$; Table 4). The southeast and northwest regions had significantly lower mean MEI compared to the southwest and central lowlands. Significant regional differences in mean lake pH were observed ($P < 0.002$; Table 4). Lakes in the southeast region had significantly lower pH than all other regions. Significant regional differences in mean Ca was observed ($P < 0.0001$; Table 4). Mean Ca in the southeast region

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was significantly lower than all other regions; mean Ca in the central lowlands and southwest regions were significantly higher from those in the southeast and northeast. Mean COND and alkalinity were significantly different among regions ($P<0.0001$; Table 4); mean COND and alkalinity in the southeast were lower compared to all other regions. Mean Mg in the southeast and northeast regions were significantly lower than other regions ($P<0.0001$; Table 4). Significant regional differences in mean lake DOC were observed ($P<0.0001$; Table 4). Lakes in the southeast and northeast regions had significantly lower DOC values compared to the northwest, central lowlands, and southwest.

DISCUSSION

In our study, largemouth bass EHg was most strongly influenced by variables related to water acidity (pH, alkalinity) and hardness (Ca, Mg, COND). The inverse relationships between mercury concentrations in fish muscle tissue and measures of acidity and hardness are consistent with findings of numerous studies examining the role of environmental factors regulating mercury accumulation in fish (Wiener et al. 1990; Wren et al. 1991; Lange et al. 1993; Wiener and Spry 1996). Increased accumulation of methylmercury in fish from low-pH waters has been attributed, in part, to greater in-lake microbial production (Wiener and Spry 1996). The role of alkalinity and pH in mercury accumulation has become a major ecological concern due to the effects of lake acidification (McMurtry et al. 1989; Wiener et al. 1990; Lange et al. 1993). Akielaszeck and Haines (1981) explained acid precipitation in New York and Maine may reduce the buffering capacity of lakes, thus lowering their alkalinity and pH causing increased mercury methylation rates. Our results suggest, as in other studies, that water acidity and hardness may play an influential role in controlling mercury methylation rates in Connecticut lakes. In our study, EHg was most strongly correlated with pH, Ca, and COND. Wiener et al. (1990) stated that Ca may be a more consistent chemical indicator of mercury concentration in fish rather than pH because of seasonal and diurnal variations in pH. Our results suggest that COND may also be used as a consistent chemical indicator of mercury in largemouth bass.

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Previous research indicated that calcium was an important factor governing metal regulation by aquatic organisms and thus may be important in determining mercury levels in fish (Wren and MacCrimmon 1983). Rodgers and Beamish (1983) found using rainbow trout *Oncorhynchus mykiss* under controlled laboratory conditions that direct uptake of methylmercury (i.e., across gill membranes) in soft water was more than double the uptake measured in hard water. The assimilation rate of waterborne methylmercury passing over the gills of fish is estimated to be only 7 to 12% (Rodgers 1994). This is relatively low compared to the estimated 65 to 85% or greater assimilation rate of methylmercury through dietary uptake (Rodgers 1994). High Ca levels or hard water therefore, may be more important as a potential inhibitor of methylmercury production and accumulation fish, rather than causing mercury uptake directly from water. Currently, no studies have been undertaken comparing concentrations of methylmercury uptake by fish through diet and water in natural systems (Wiener and Spry 1996).

The potential increase in mercury methylation rates in low-pH lakes might be partly explained by lake redox potentials. A significant positive correlation between EHg and lake redox potential was found in our study. Wood (1980) predicted that a combination of low pH and high redox potential would be optimal for mercury methylation in the water column and at the sediment surface. Mercury methylation in sediments was highest at a pH of 6.0 (Suns and Hitchin 1990) which is an upper level typical of acidified water bodies.

Much evidence points to atmospheric inputs of mercury, either directly to lake surfaces (Wiener et al. 1990; Fitzgerald et al. 1991) or indirectly via their watersheds (McMurtry et al. 1989; Suns and Hitchin 1990), in determining methylmercury levels in fish. In our multiple regression models explaining EHg, the negative coefficient of lake surface area and the positive coefficient of watershed area suggests that increased mercury levels in largemouth bass might be influenced by mercury loading from large watershed areas that drain into small water surfaces of our study lakes. McMurtry et al. (1989), Suns and Hitchin (1990), and Bodaly et al. (1993) found that the watershed size/lake volume ratio was directly related to mercury levels in fish. However, ratios of watershed area lake area or watershed area/lake volume were not significantly correlated with EHg in this study. Our results suggest that the

watershed area-lake surface area loading factor may be secondary to other variables representing acid-neutralizing capacity and hardness, which appear to be the lead indicators of largemouth bass EHg in Connecticut lakes.

The lake watershed-surface area loading factor together with the increasing empirical evidence that DOC is linked with mercury levels in fish (Grieb et al. 1990; Wren et al. 1991) provides insight to our findings. Fish mercury levels have been positively correlated with DOC levels (McMurtry et al. 1989; Wren et al. 1991); in this study largemouth bass EHg was overall negatively correlated with DOC based on individual regressions. However, the coefficient for DOC in our multiple regression models was positive suggesting that increasing DOC levels may be positively influencing EHg only under certain water hardness conditions. Grieb et al. (1990) showed that the wide variability in the pH-fish mercury relationship at lower pH ranges could be explained by DOC concentrations in their study lakes. Grieb et al. (1990) speculated that reductions in fish mercury concentration at higher DOC levels might be due to methylmercury binding with organic molecules, thus, inhibiting uptake by fish. However, evidence suggests that fish mercury concentrations may also be positively linked to DOC (McMurtry et al. 1989). Humic substances may act as a source of mercury for methylating bacteria (Bodaly et al. 1984). These humic materials might mobilize mercury from the watershed and act as a source of methylmercury to aquatic systems (Mierle 1990). As did we, Wren et al. (1990) found that Ca and DOC were significant in explaining mercury levels in northern pike and walleye in Ontario Lakes. However, in their study lakes, DOC provided a greater influence on fish mercury concentrations than found for largemouth bass EHg in our study lakes. In our study lakes, measures of acidity and hardness appeared to be the primary factors affecting EHg. The role of DOC in influencing EHg in Connecticut lakes remains unclear.

In our multiple regression model, EHg in largemouth bass was positively influenced by lake maximum depth. Lake depth has been shown to be inversely related to lake productivity (Rawson 1953; Hayes 1957). In our study lakes, lake maximum depth was inversely related to measures of lake productivity such as MEI ($r=-0.62$, $P=0.0001$), and total dissolved phosphorus ($r=-0.25$, $P=0.07$). Wren and MacCrimmon (1983) also found that lake

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maximum depth was an important variable explaining mercury levels in pumpkinseed. They speculated that maximum depth was related to lake productivity, thus influencing the availability of mercury in the ecosystems. Bioaccumulation of mercury in fish may be elevated in less productive lakes because mercury may become concentrated in the small amount of biomass produced annually (Joslin 1994). In our study, EHg was significantly inversely correlated with MEI and particulate phosphorus.

The ecoregion delineations used in this study appeared to be valuable for detecting regional differences in largemouth bass mercury concentrations within the state, and for identifying environmental characteristics on a regional scale that may be potentially contributing to variability of mercury concentrations among regions. Regional variations in bedrock geology may be the primary reason for the observed regional variations in largemouth bass mercury concentrations. As in other studies, our results suggest that largemouth bass mercury concentrations appear to be influenced mostly by those variables contributing to acid neutralizing capacity (pH, alkalinity) and water hardness (COND, Ca, Mg). Mean EHg was higher in the southeastern region of the state, followed by the northeast, northwest, southwest, and central lowlands. The eastern uplands are generally underlain by metamorphic and igneous bedrock; these crystalline rocks are composed or relatively insoluble silicate materials (Trench 1996). In these areas, stream water is typically soft and slightly acidic, and concentrations of total dissolved solids is low compared to other regions. The western uplands are underlain by similar insoluble crystalline rock; however, an area along the western border and in the northwestern corner of the state includes a marble belt composed of soluble carbonate materials (Trench 1996). In the western uplands, stream water concentrations of dissolved solids are relatively high, water is slightly alkaline, and hardness varies from soft to hard. The central lowlands are underlain primarily by arkosic sedimentary rock that are more easily eroded and are more susceptible to chemical weathering than the igneous and crystalline rocks of the eastern and western uplands. Streams draining these areas are typically high in dissolved solids, and pH in these areas ranges from slightly acidic to slightly alkaline (Trench 1996).

Our lake samples, specifically pH, alkalinity, conductivity, Ca, and Mg varied among

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ecoregions based on bedrock geology. Lakes in the eastern uplands region were relatively lower in pH, alkalinity, conductivity, Ca, and Mg, and largemouth bass mercury concentrations were typically higher than the western uplands or central lowlands regions. Lakes in the western uplands and central lowlands regions were relatively moderate to high in pH, alkalinity, conductivity, Ca, and Mg, and largemouth bass mercury concentrations were typically lower in these regions. Although the southwest and central lowlands regions are the most highly urbanized areas of the state, the relatively low largemouth bass mercury concentrations observed in lakes from those regions suggest that other environmental factors, such as those influenced by bedrock geology (acidity and hardness), play a more important role in affecting mercury availability and accumulation.

Preliminary Tests of Predictive Utility

Five additional lakes, independent of our study lakes, were used to test whether the independent variable models that we found to be significant, accurately predicted EHg in largemouth bass (EHg range = 0.346 - 0.512 μg/g). We found that the correlation between predicted mercury concentration and EHg was strongest using the model for COND ($r^2 = 0.96$, $P = 0.004$), and the slope of the relationship was near one (slope = 1.22), indicating a 1:1 relationship between predicted mercury and EHg. These results provide preliminary evidence that measures of acidity and water hardness may be the primary factors influencing largemouth bass mercury concentrations in Connecticut lakes, although multiple variables were useful in explaining variability in EHg in the large set of our study lakes.

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Table 1. Correlations between expected mercury concentrations in 356-mm largemouth bass (*E*Hg) with environmental attributes of Connecticut lakes, 1995. Intercept (*a*) and slope (*b*) values are included for those regressions that were significant (*P*<0.05).

Attribute	N	Mean	Range	a	b	r	P
*E*Hg (μg/g wet weight)[a]	51	0.433	0.102-1.115				
Lake volume (m³)[b]	51	389	2-13928			0.01	0.93
Retention time (d)[c]	51	439.2	0.6-5621.0			0.03	0.82
Maximum depth (m)[c]	51	11.9	1.5-37.5			0.09	0.53
Mean depth (m)[c]	51	4.9	0.9-12.8			-0.02	0.86
Secchi depth (m)[c]	48	2.6	0.4-6.8			0.22	0.14
Watershed area (ha)[b]	51	25760.6	71.2-406766.2			0.00	0.97
Surface area (ha)[b]	51	145.8	10.4-2057.8			-0.11	0.44
Perimeter (m)[b]	51	11617	1331-116571			0.08	0.56
Watershed area/lake area ratio[c]	51	208.2	3.1-2902.8			-0.09	0.51
Watershed area/lake volume ratio[b]	51	69.501	0.002-1270.720			0.00	0.97
Shoreline development index[b]	51	2.83	0.28-14.42			0.21	0.15
Elevation (m)[d]	51	141	18-386			-0.26	0.07
Morphoedaphic index (MEI)[b]	49	25.9	4.2-125.7	-0.103	-0.234	-0.42	0.003
pH[b]	49	7.49	6.69-8.84	2.692	-3.535	-0.50	0.0003
Specific conductivity (μS/cm)[b]	49	137	33-306	0.325	-0.352	-0.51	0.0002

Table 1., continued.   Correlations between expected mercury concentrations in 356-mm largemouth bass (*EHg*) with environmental attributes of Connecticut lakes, 1995.   Intercept (*a*) and slope (*b*) values are included for those regressions that were significant ($P < 0.05$).

Attribute	N	Mean	Range	a	b	r	P
Redox potential (mV)[b]	49	370	334-468	-5.573	2.017	0.30	0.03
Nitrate+nitrite (mg/L)[b]	49	0.178	0.001-3.308			-0.27	0.06
Ammonia (mg/L)[b]	49	0.044	0			-0.04	0.81
Total dissolved nitrogen (mg/L)[e]	49	0.596	0.175-4.504			0.18	0.21
Dissolved inorganic phosphorus (mg/L)[b]	49	0.026	0.001-0.471			-0.26	0.07
Total dissolved phosphorus (mg/L)[b]	49	0.033	0.003-0.422			-0.21	0.15
Alkalinity (mg/L)[d]	49	33	1-132	-0.174	-0.164	-0.36	0.01
Dissolved organic carbon (mg/L)[b]	49	13.4	4.0-42.5	-0.131	-0.253	-0.34	0.02
Total suspended solids (mg/L)[b]	49	11.48	0.001-275.000			-0.16	0.28
Particulate phosphorus (mg/L)[b]	49	0.0351	0.0005-0.2800	-0.623	-0.130	-0.32	0.02
Particulate carbon (mg/L)[e]	49	1.52	0.544-7.201			0.20	0.16
Particulate nitrogen (mg/L)[b]	49	0.228	0.022-0.850			-0.07	0.62
Calcium (µg/L)[b]	50	10990.5	1622.0-34036.0	0.594	-0.255	-0.50	0.0002

Table 1., continued. Correlations between expected mercury concentrations in 356-mm largemouth bass (EHg) with environmental attributes of Connecticut lakes, 1995. Intercept (*a*) and slope (*b*) values are included for those regressions that were significant (P<0.05).

Attribute	N	Mean	Range	*a*	*b*	*r*	*P*
Magnesium (μg/L)[b]	50	3940.1	573.0-19682	0.313	-0.207	-0.41	0.0032

[a]Based on $\log_{10}$ Hg concentration-$\log_{10}$ length regressions.
[b]Correlation based on transformed ($\log_{10}$) data.
[c]Correlation based on transformed ($\log_{10}$ + 1) data.
[d]Correlation based on transformed (square root) data.
[e]Correlation based on transformed (inverse) data.
[f]Lake volume expressed as m^3 x 10^{-5}.

Table 2. Pearson correlation coefficients for lake chemical variables collected from Connecticut lakes 1995. All correlation coefficients were significant at $P < 0.0001$.

	Calcium	Magnesium	Specific Conductivity	Alkalinity
pH	0.67	0.62	0.60	0.57
Calcium		0.94	0.93	0.84
Magnesium			0.89	0.86
Specific Conductivity				0.86

Table 3. Stepwise regressions with physical, chemical, and physical and chemical variables entered versus EHg levels in largemouth bass. All variables were significant at $P < 0.05$. Partial r^2 values are given for individual variables.

Physical model		Chemical model		Physical and chemical model	
Variables	r^2	Variables	r^2	Variables	r^2
MEI[a]	0.173	Ca[c]	0.253	Ca	0.253
SA[b]	0.072	DOC[d]	0.061	DOC	0.061
				SA	0.058
				MXD[e]	0.074
				WA[f]	0.080
Model R^2 0.25		0.31		0.53	

[a] MEI = morphoedaphic index
[b] SA = surface area
[c] Ca = calcium
[d] DOC = dissolved inorganic carbon
[e] MXD = maximum depth
[f] WA = watershed area

Table 4. Regional comparisons of physical and chemical characteristics from Connecticut lakes, 1995. Statistical analyses were performed using transformed values (see Table 1 for transformations used on individual variables). Nontransformed means and SE are displayed. Means followed by the same letter within rows are not significantly different ($P > 0.05$) based on Fishers LSD test (NS= not significant).

Variable	Southeast Mean(SE)	Northeast Mean(SE)	Northwest Mean(SE)	Southwest Mean(SE)	Central Mean(SE)	P
EHg	0.577(0.06)[c]	0.461(0.05)[bc]	0.405(0.06)[ab]	0.382(0.05)[ab]	0.324(0.05)[a]	0.008
Maximum depth	10.6(1.53)	9.1(0.83)	15.3(3.04)	14.5(3.30)	9.9(3.27)	NS
Watershed area	2.39(1.09)	27.51(20.59)	4.12(1.71)	75.33(48.86)	21.60(16.56)	NS
Surface area	102.8(23.53)	112.9(21.32)	178.9(33.42)	267.7(181.62)	59.8(15.68)	NS
Morphoedaphic index	11.1(1.30)[a]	20.3(3.99)[ab]	13.9(2.31)[a]	33.6(8.10)[bc]	61.6(17.02)[c]	0.0001
pH	7.09(0.05)[a]	7.49(0.15)[b]	7.72(0.18)[b]	7.58(0.11)[b]	7.82(0.24)[b]	0.0016
Specific Conductivity	59(6.10)[a]	104(13.22)[b]	140(26.99)[b]	210(22.73)[c]	213(24.64)[c]	0.0001
Redox Potential	385(8.51)[b]	365(5.26)[ab]	379(4.80)[b]	348(8.46)[a]	368(5.76)[b]	0.0043
Alkalinity	9(1.25)[a]	22(4.71)[b]	53(15.32)[bc]	42(6.96)[bc]	54(5.23)[c]	0.0001
Dissolved organic carbon	6.6(0.42)[a]	9.1(1.38)[a]	20.1(4.27)[b]	16.9(1.91)[b]	17.7(2.52)[c]	0.0001
Particulate phosphorus	0.0133(0.005)[a]	0.0325(0.013)[ac]	0.0214(0.004)[ab]	0.0507(0.026)[bc]	0.0718(0.029)[c]	0.017
Calcium	3.46(0.51)[a]	7.25(1.57)[b]	13.63(3.41)[bc]	14.65(2.02)[c]	19.91(3.34)[c]	0.0001
Magnesium	1.22(141.21)[a]	1.77(.22)[a]	7.37(2.31)[b]	5.33(.77)[b]	5.10(.90)[b]	0.0001
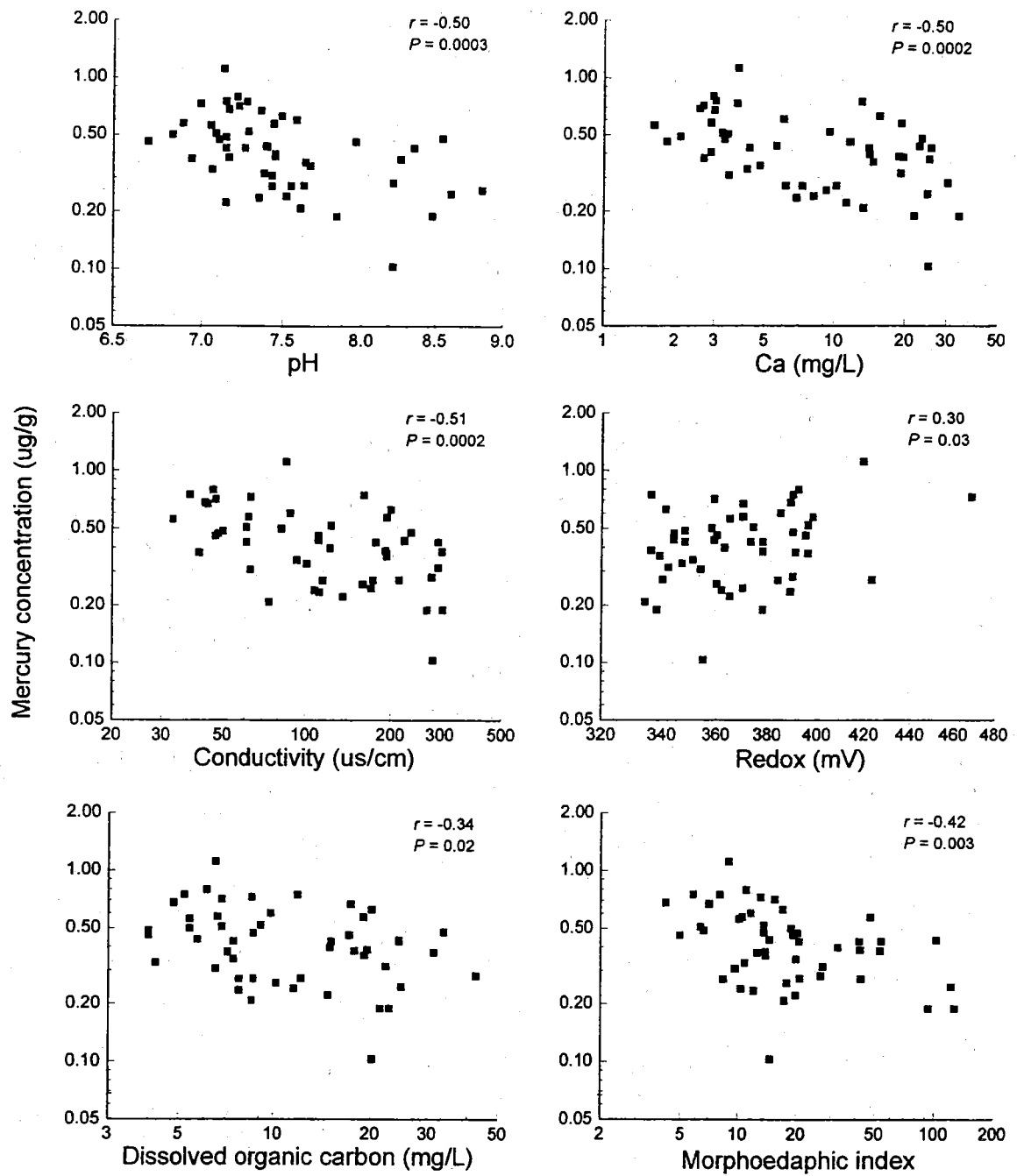
Figure 1. Relationships between mercury concentrations (ug/g wet weight) predicted for a 356 mm fish and selected environmental attributes of Connecticut lakes.

Appendix 1. Lake physical parameters measured during this study or obtained from, CTDEP (1982, 1987, and 1991), Handman et al. (1986), Heally and Kulp (1995), Ryder et al. (1995), Thomas et al. (1967), Thomas et al. (1970), Thomas et al. (1968), Weiss et al. (1974), and geographical information systems database through assistance of staff at the Natural Resource Center of the CTDEP (Retime=retention time, Maxdepth, Mndepth=mean depth, Sedepth=Secchi depth, Wsarea=watershed area).

Location	Retime	Maxdepth	Mndepth	Sedepth	Volume	Wsarea
	days	m	m	m	m³	ha
Amos Lake	657	14.6	5.8	3.2	2,476,380	372.2
Aspinook Pond	1	8.2	2.7	0.6	4,456,754	167,202.6
Ball Pond	1,716	15.8	6.9	2.9	2,517,484	99.5
Bantam Lake	106	7.6	4.4	2.0	16,157,105	8,483.0
Bashan Lake	5,621	14.6	4.9	3.8	54,194,990	508.7
Batterson Park Pond	157	6.1	4.5	-	2,970,170	1,073.3
Beach Pond	412	19.8	6.1	3.3	9,775,858	1,217.3
Billings Lake	511	10.0	4.2	4.5	1,776,251	179.5
Black Pond	128	7.0	2.6	2.0	801,959	304.3
Bolton Lake	110	7.9	3.0	2.6	3,875,520	2,263.1
Canoe Brook Lake	14	9.1	2.7	3.4	1,109,005	475.3
Candlewood Lake	1,205	25.9	8.9	1.7	196,000,000	10,484.3
Cedar Swamp Pond	360	4.3	2.6	1.2	1,426,221	232.1
Coventry Lake	986	12.2	8.8	3.6	13,500,000	767.2
Crystal Lake- Ellington	442	15.2	6.0	2.9	4,856,999	730.6
Crystal Lake- Middletown	267	7.3	2.4	2.0	345,000	71.2
Dodge Pond	292	14.6	6.1	3.1	814,097	149.4
East Twin Lake	1,533	24.4	9.9	3.0	22,472,000	1,068.1

Appendix 1, continued. Lake physical parameters measured during this study or obtained from, CTDEP (1982, 1987, and 1991), Handman et al. (1986), Heally and Kulp (1995), Ryder et al. (1970), Thomas et al. (1967), Thomas et al. (1968), Weiss et al. (1982), Wilson et al. (1974), and geographical information systems database through assistance of staff at the Natural Resource Center of the CTDEP (Retime=retention time, Maxdepth, Mndepth=mean depth, Sedepth=Secchi depth, Wsarea=watershed area).

SITE	Retime days	Maxdepth m	Mndepth m	Sedepth m	Volume m³	Wsarea ha
Gardner Lake	320	13.1	4.2	2.4	8,226,000	1,431.2
Glasgo Pond	15	7.6	3.1	1.4	2,272,327	9,802.4
Hannover Pond	1	2.7	1.4	0.9	390,986	24,633.2
Highland Lake	285	18.9	6.0	3.7	10,789,001	1,813.5
Housatonic Lake	1	7.9	2.9	2.0	3,201,077	406,766.2
Lake Kenosia	39	4.6	3.5	1.2	793,775	1,304.6
Lake of Isles	224	3.0	1.9	3.0	655,000	174.1
Lake Mamanasco	219	3.0	2.1	1.8	808,546	364.7
Mansfield Hollow Reservoir	45	6.9	4.9	1.5	30,850,000	42,387.9
Lake Mashapaug	161	13.1	2.8	5.0	3,371,495	1,186.7
Lake McDonough	39	18.0	6.6	4.1	11,120,330	16,121.7
Moodus Reservoir	53	3.1	1.5	1.4	2,718,483	2,683.0
Mudge Pond	135	10.7	6.7	2.1	5,454,448	2,979.0
North Farms Reservoir	69	1.5	0.9	0.4	238,987	197.6
Pachaug Pond	25	5.5	1.9	2.2	6,251,880	13,553.0
Pattagansett Lake	110	10.4	3.8	1.9	1,881,303	996.9
Powers Lake	300	4.0	2.1	2.5	1,317,752	257.7

Appendix 1, continued. Lake physical parameters measured during this study or obtained from, CTDEP (1982, 1987, and 1991), Handman et al. (1986), Heally and Kulp (1995), Ryder et al. (1970), Thomas et al. (1967), Thomas et al. (1968), Weiss et al. (1982), Wilson et al. (1974), and geographical information systems database through assistance of staff at the Natural Resource Center of the CTDEP (Retime=retention time, Maxdepth, Mndepth=mean depth, Sedepth=Secchi depth, Wsarea=watershed area).

SITE	Retime days	Maxdepth m	Mndepth m	Sedepth m	Volume m³	Wsarea ha
Quaddick Reservoir	33	7.6	2.0	2.2	3,685,462	5,908.8
Lake Qussapaug	1,252	19.8	8.7	6.8	9,526,000	479.7
Rainbow Reservoir	1	15.2	5.7	1.1	2,846,875	152,156.3
Rogers Lake	190	20.1	6.1	3.2	6,567,651	1,956.0
Lake Saltonstall	376	32.4	12.3	2.7	20,817,500	1,020.5
Saugatuck Reservoir	303	37.5	12.8	-	45,132,340	8,933.7
Silver Lake	91	3.7	1.4	2.2	838,150	517.7
Taunton Lake	602	9.0	6.6	3.9	3,341,497	330.5
Tyler Lake	99	8.0	3.7	1.7	2,716,369	1,686.1
Union Pond	2	4.9	3.7	-	379,310	13,765.3
Lake Waramaug	310	12.2	6.7	2.0	18,542,186	3,722.6
Wauregan Reservoir	282	9.5	4.9	2.8	1,390,000,000	325.8
Lake Winchester	337	4.9	4.0	3.0	3,672,000	586.4
Wonoskopomuc	1,712	32.9	11.1	2.6	15,787,000	656.1
Wyassup Lake	248	8.5	2.7	5.1	1,014,364	220.2
Lake Zoar	4	22.9	7.5	1.7	28,585,013	399,191.8

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Appendix 1, continued. Lake physical parameters were obtained or calculated during this study from, CTDEP (1982, 1987, and 1991), Handman et al. (1986), Heally and Kulp (1995), Hydrolab (1995), Ryder et al. (1970), Thomas et al. (1967), Thomas et al. (1968), Weiss et al. (1982), Wilson et al. (1974), and geographical information systems database through assistance of staff at the Natural Resource Center of the CTDEP (Sarea=lake surface area, Perim=lake perimeter, Wslarat=watershed area/lake area ratio, Wsvorat=watershed area/lake volume ratio, SDI=shoreline development index, Elev=elevation, MEI=Morphoedaphic index).

SITE	Sarea	Perim	Wslarat	Wsvorat	SDI	Elev	MEI
	ha	m	unitless	unitless	unitless	m	unitless
Amos Lake	45.5	4,185	8.2	1.500	1.75	40	13.6
Aspinook Pond	125.0	20,985	1,337.8	375.170	5.30	296	41.7
Ball Pond	32.7	2,830	3.1	0.400	1.40	237	27.3
Bantam Lake	386.6	15,143	21.9	5.250	2.17	272	19.8
Bashan Lake	107.5	9,507	4.7	0.090	2.59	118	6.6
Batterson Park Pond	58.9	3,641	18.2	3.610	1.34	94	-
Beach Pond	141.0	11,156	8.6	1.250	2.65	90	4.9
Billings Lake	38.4	6,526	4.7	1.010	2.97	108	5.8
Black Pond	30.6	3,806	10.0	3.790	1.94	116	47.5
Bolton Lake	128.3	10,461	17.6	5.840	2.60	203	19.8
Canoe Brook Lake	25.8	4,095	18.4	4.290	2.28	91	17.3
Candlewood Lake	2,057.7	116,571	5.1	0.540	7.25	131	13.9
Cedar Swamp Pond	54.8	5,656	4.2	1.630	2.15	272	42.6
Coventry Lake	151.5	9,366	5.1	0.570	2.15	157	8.4
Crystal Lake- Ellington	75.8	4,823	9.6	1.500	1.56	194	10.8
Crystal Lake- Middletown	12.5	3,624	5.7	2.060	2.89	30	32.5
Dodge Pond	12.0	1,565	12.5	1.840	1.28	18	8.9

Appendix 1, continued. Lake physical parameters were obtained or calculated during this study from, CTDEP (1982, 1987, and 1991), Handman et al. (1986), Healy and Kulp (1995), Hydrolab (1995), Ryder et al. (1970), Thomas et al. (1967), Thomas et al. (1968), Weiss et al. (1982), Wilson et al. (1974), and geographical information systems database through assistance of staff at the Natural Resource Center of the CTDEP (Sarea=lake surface area, Perim=lake perimeter, Wslarat=watershed area/lake area ratio, Wsvorat=watershed area/lake volume ratio, SDI=shoreline development index, Elev=elevation, MEI=Morphoedaphic index).

SITE	Sarea	Perim	Wslarat	Wsvorat	SDI	Elev	MEI
	ha	m	unitless	unitless	unitless	m	unitless
East Twin Lake	228.8	10,561	4.7	0.480	1.97	223	12.5
Gardner Lake	213.4	9,639	6.7	1.740	1.86	116	9.6
Glasgo Pond	74.5	10,058	131.5	43.140	3.29	56	13.0
Hannover Pond	28.5	3,548	863.1	630.030	1.87	265	125.7
Highland Lake	181.4	1,331	10.0	1.680	0.28	269	11.9
Housatonic Lake	140.1	21,289	2,902.8	1,270.720	5.07	61	42.2
Lake Kenosia	23.0	2,718	56.8	16.440	1.60	137	53.8
Lake of Isles	36.9	6,165	4.7	2.660	2.86	78	13.8
Lake Mamanasco	34.8	3,536	10.5	4.510	1.69	176	93.3
Mansfield Hollow Reservoir	178.5	2,212	237.5	13.740	0.47	64	11.6
Lake Mashapaug	120.6	12,923	9.8	3.520	3.32	215	18.7
Lake McDonough	156.1	17,290	103.3	14.500	3.90	128	4.2
Moodus Reservoir	178.4	19,837	15.0	9.870	4.19	109	20.2
Mudge Pond	81.3	4,384	36.6	5.460	1.37	163	26.7
North Farms Reservoir	26.7	3,354	7.4	8.270	1.83	101	120.9
Pachaug Pond	50.9	6,006	19.6	5.300	2.38	192	10.4
Pattagansett Lake	330.6	21,374	41.0	21.680	3.32	48	20.5

Appendix 1, continued. Lake physical parameters were obtained or calculated during this study from, CTDEP (1982, 1987, and 1991), Handman et al. (1986), Heally and Kulp (1995), Hydrolab (1995), Ryder et al. (1970), Thomas et al. (1967), Thomas et al. (1968), Weiss et al. (1982), Wilson et al. (1974), and geographical information systems database through assistance of staff at the Natural Resource Center of the CTDEP (Sarea=lake surface area, Perim=lake perimeter, Wslarat=watershed area/lake area ratio, Wsvorat=watershed area/lake volume ratio, SDI=shoreline development index, Elev=elevation, MEI=Morphoedaphic index).

SITE	Sarea	Perim	Wslarat	Wsvorat	SDI	Elev	MEI
	ha	m	unitless	unitless	unitless	m	unitless
Powers Lake	59.3	5,419	4.4	1.960	1.99	48	10.1
Quaddick Reservoir	158.4	22,049	37.3	16.030	4.94	123	15.4
Lake Qussapaug	120.1	10,117	4.0	0.500	2.60	212	-
Rainbow Reservoir	82.7	17,768	1,840.4	534.470	5.51	21	17.9
Rogers Lake	111.4	10,550	17.6	2.980	2.82	110	6.4
Lake Saltonstall	167.3	12,354	6.1	0.490	2.69	73	14.7
Saugatuck Reservoir	33.3	29,497	268.2	1.980	14.42	86	8.0
Silver Lake	56.9	6,001	9.1	6.180	2.24	46	101.9
Taunton Lake	50.4	3,699	6.6	0.990	1.47	165	20.8
Tyler Lake	75.8	5,717	22.3	6.210	1.85	386	19.2
Union Pond	10.4	2,626	1,329.8	362.910	2.30	45	53.2
Lake Waramaug	259.3	14,905	14.4	2.010	2.61	212	10.3
Wauregan Reservoir	28.8	3,045	11.3	0.002	1.60	60	14.6
Lake Winchester	100.4	8,984	5.8	1.600	2.53	381	7.0
Wonoskopomuc	140.9	4,687	4.7	0.420	1.11	221	13.6
Wyassup Lake	40.0	5,075	5.5	2.170	2.26	92	10.9
Lake Zoar	372.5	39,812	1,071.8	139.650	5.82	31	17.0

Appendix 2. Water quality parameters were analyzed with a Hydrolab multiprobe and by the Environmental Research Institute; samples were collected or measured at 1-m subsurface from Connecticut water bodies, 1995 (SpCond=specific conductivity; Redox=redox potential; NOX=nitrate+nitrite; NH$_3$=ammonia; TDN=total dissolved nitrogen; DIP=dissolved inorganic phosphorus).

Location	pH	SpCond µS/cm	Salinity ppt	Redox mV	NOX mg/L	NH$_3$ mg/L	TDN mg/L	DIP mg/L
Amos Lake	7.28	123	0.1	396	0.004	0.005	0.252	0.002
Aspinook Pond	8.35	176	0.1	373	0.008	0.001	0.433	0.004
Ball Pond	7.38	294	0.1	342	0.018	0.130	0.535	0.006
Bantam Lake	7.14	136	0.1	365	0.037	0.002	0.339	0.003
Bashan Lake	7.14	50	0.0	348	0.001	0.011	0.370	0.010
Batterson Park Pond	-	-	-	-	-	-	-	-
Beach Pond	6.69	47	0.0	395	0.004	0.001	0.256	0.002
Billings Lake	7.14	38	0.0	390	0.001	0.006	0.436	0.001
Black Pond	7.44	193	0.1	398	0.005	0.016	0.517	0.032
Bolton Lake	7.67	93	0.0	351	0.003	0.009	0.238	0.001
Canoe Brook Lake	7.61	74	0.0	334	0.281	0.015	0.497	0.003
Candlewood Lake	7.64	193	0.1	339	0.040	0.058	0.315	0.003
Cedar Swamp Pond	7.55	173	0.1	423	0.001	0.002	0.275	0.001
Coventry Lake	7.43	115	0.0	384	0.014	0.015	0.407	0.002
Crystal Lake- Ellington	7.06	101	0.0	347	0.033	0.027	0.175	0.010
Crystal Lake- Middletown	7.45	122	0.1	363	0.037	0.044	0.570	0.001
Dodge Pond	7.13	85	0.0	419	0.021	0.001	0.340	0.001
East Twin Lake	8.26	193	0.1	396	0.001	0.001	0.513	0.003

Appendix 2, continued. Water quality parameters were analyzed with a Hydrolab multiprobe and by the Environmental Research Institute; samples were collected or measured at 1-m subsurface from Connecticut water bodies, 1995 (SpCond=specific conductivity; Redox=redox potential; NOX=nitrate+nitrite; NH_3=ammonia; TDN=total dissolved nitrogen; DIP=dissolved inorganic phosphorus).

Location	pH	SpCond	Salintiy	Redox	NOX	NH_3	TDN	DIP
		µS/cm	ppt	mV	mg/L	mg/L	mg/L	mg/L
Gardner Lake	7.43	63	0.0	354	0.001	0.005	0.360	0.007
Glasgo Pond	6.99	63	0.0	468	0.010	0.006	0.281	0.002
Hannover Pond	7.84	269	0.1	378	3.308	0.001	3.890	0.471
Highland Lake	7.35	112	0.0	389	0.002	0.001	0.295	0.001
Housatonic Lake	7.45	191	0.1	336	0.328	0.029	0.578	0.024
Lake Kenosia	7.26	294	0.1	348	0.066	0.161	0.635	0.004
Lake of Isles	6.94	41	0.0	391	0.120	0.009	0.536	0.001
Lake Mannanasco	8.48	306	0.1	338	0.010	0.001	0.349	0.007
Mansfield Hollow Reservoir	7.58	88	0.0	385	0.012	0.009	0.312	0.007
Lake Mashapaug	6.83	82	0.0	358	0.004	0.012	0.419	0.015
Lake McDonough	7.16	43	0.0	389	0.002	0.004	0.275	0.002
Moodus Reservoir	7.10	48	0.0	344	0.001	0.001	0.491	0.013
Mudge Pond	8.21	279	0.1	390	0.006	0.001	0.416	0.002
North Farms Reservoir	8.61	170	0.1	370	0.004	0.001	1.063	0.058
Pachaug Pond	7.14	61	0.0	378	0.003	0.001	0.230	0.002
Pattagansett Lake	6.89	62	0.0	370	0.021	0.001	0.228	0.001
Powers Lake	7.05	33	0.0	365	0.024	0.001	0.377	0.001
Quaddick Reservoir	7.22	47	0.0	359	0.001	0.007	0.433	0.006

Appendix 2, continued. Water quality parameters were analyzed with a Hydrolab multiprobe and by the Environmental Research Institute; samples were collected or measured at 1-m subsurface from Connecticut water bodies, 1995 (SpCond=specific conductivity; Redox=redox potential; NOX=nitrate+nitrite; NH$_3$=ammonia; TDN=total dissolved nitrogen; DIP=dissolved inorganic phosphorus).

Location	pH	SpCond µS/cm	Salinity ppt	Redox mV	NOX mg/L	NH$_3$ mg/L	TDN mg/L	DIP mg/L
Lake Qussapaug	-	-	-	-	-	-	-	-
Rainbow Reservoir	8.84	159	0.1	360	0.810	0.001	1.089	0.131
Rogers Lake	7.08	61	0.0	374	0.024	0.001	0.346	0.001
Lake Saltonstall	8.21	282	0.1	355	0.092	0.068	0.404	0.006
Saugatuck Reservoir	7.27	160	0.1	336	0.038	0.030	0.294	0.006
Silver Lake	7.40	223	0.1	359	0.152	0.108	1.233	0.107
Taunton Lake	7.63	214	0.1	340	0.074	0.215	0.493	0.023
Tyler Lake	7.96	111	0.0	360	0.005	0.010	0.466	0.005
Union Pond	7.16	304	0.1	378	2.706	1.024	4.504	0.255
Lake Waramaug	7.52	108	0.0	362	0.010	0.022	0.420	0.005
Wauregan Reservoir	7.39	111	0.0	344	0.008	0.001	0.305	0.002
Lake Winchester	7.36	44	0.0	370	0.008	0.024	0.491	0.002
Wonoskopomuc	8.55	235	0.1	390	0.013	0.001	0.472	0.005
Wyassup Lake	7.21	46	0.0	392	0.005	0.014	0.398	0.002
Lake Zoar	7.49	199	0.1	341	0.361	0.034	0.671	0.024

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Appendix 2, continued. Water quality parameters were analyzed with a Hydrolab multiprobe and by the Environmental Research Institute; samples were collected or measured at 1-m subsurface from Connecticut water bodies, 1995 (TDP=total dissolved phosphorus; ALK=alkalinity; DOC=dissolved organic carbon; TSS=total suspended solids; PP=particulate phosphorus; PC=particulate carbon; PN=particulate nitrogen; Ca=calcium; Mg=magnesium).

Location	TDP mg/L	ALK mg/L	DOC mg/L	TSS mg/L	PP mg/L	PC mg/L	PN mg/L	Ca µg/L	Mg µg/L
Amos Lake	0.007	20	9.1	2.0	0.006	1.204	0.477	9550	2671
Aspinook Pond	0.017	36	15.1	19.0	0.080	3.369	0.850	14007	2762
Ball Pond	0.011	58	22.2	0.5	0.021	1.132	0.177	19094	6708
Bantam Lake	0.020	43	14.8	6.0	0.030	1.312	0.265	11261	5076
Bashan Lake	0.021	3	4.0	0.5	0.010	0.664	0.062	2111	830
Batterson Park Pond	-	-	-	-	-	-	-	-	-
Beach Pond	0.021	3	4.0	3.0	0.006	1.408	0.454	1836	573
Billings Lake	0.006	4	5.2	2.0	0.005	0.829	0.154	3017	698
Black Pond	0.024	61	19.0	6.0	0.013	1.211	0.147	19159	6231
Bolton Lake	0.017	14	7.4	1.0	0.010	0.945	0.106	4767	1459
Canoe Brook Lake	0.025	1	8.5	43.0	0.064	5.281	0.711	13323	3403
Candlewood Lake	0.008	55	19.1	0.5	0.020	1.455	0.343	14584	5805
Cedar Swamp Pond	0.008	18	8.6	8.0	0.011	1.918	0.156	6161	2001
Coventry Lake	0.011	19	7.7	1.0	0.106	0.544	0.073	7257	1547
Crystal Lake- Ellington	0.006	33	4.2	3.0	0.007	0.583	0.075	4163	1232
Crystal Lake- Middletown	0.011	42	15.0	5.0	0.016	1.184	0.104	14099	2380
Dodge Pond	0.005	12	6.5	0.5	0.066	0.817	0.240	3788	1697
East Twin Lake	0.022	96	31.3	3.0	0.015	0.970	0.131	25396	11873

Appendix 2, continued. Water quality parameters were analyzed with a Hydrolab multiprobe and by the Environmental Research Institute; samples were collected or measured at 1-m subsurface from Connecticut water bodies, 1995 (TDP=total dissolved phosphorus; ALK=alkalinity; DOC=dissolved organic carbon; TSS=total suspended solids; PP=particulate phosphorus; PC=particulate carbon; PN=particulate nitrogen; Ca=calcium; Mg=magnesium).

Location	TDP mg/L	ALK mg/L	DOC mg/L	TSS mg/L	PP mg/L	PC mg/L	PN mg/L	Ca µg/L	Mg µg/L
Gardner Lake	0.021	10	6.5	1.0	0.012	1.140	0.140	3466	1181
Glasgo Pond	0.010	11	8.5	8.0	0.010	1.302	0.116	3749	1302
Hannover Pond	0.422	66	21.3	9.0	0.062	1.223	0.147	34036	5199
Highland Lake	0.003	15	7.7	0.5	0.025	0.790	0.102	6854	2323
Housatonic Lake	0.041	57	19.5	14.0	0.016	0.715	0.100	18761	7201
Lake Kenosia	0.029	64	24.4	23.0	0.024	1.574	0.356	25794	9408
Lake of Isles	0.008	9	7.1	2.0	0.006	1.520	0.228	2680	1000
Lake Mamanasco	0.006	59	22.8	0.5	0.009	0.745	0.289	21841	8057
Mansfield Hollow Reservoir	0.027	20	9.8	5.0	0.008	0.850	0.058	6207	2186
Lake Mashapaug	0.010	33	5.4	3.0	0.015	1.026	0.137	3426	1604
Lake McDonough	0.007	9	4.8	0.5	0.001	0.699	0.087	2565	940
Moodus Reservoir	0.027	12	8.6	1.0	0.037	1.673	0.193	3311	1175
Mudge Pond	0.023	132	42.5	2.0	0.020	1.148	0.163	30287	19682
North Farms Reservoir	0.110	61	24.8	23.0	0.353	7.201	0.785	24884	4993
Pachaug Pond	0.006	12	7.4	3.0	0.004	0.911	0.080	4256	1456
Pattagansett Lake	0.014	6	6.6	3.0	0.008	1.060	0.128	2889	1456
Powers Lake	0.010	4	5.4	4.0	0.006	1.147	0.128	1622	753
Quaddick Reservoir	0.005	7	6.8	0.5	0.010	0.895	0.066	2663	786

Appendix 2, continued. Water quality parameters were analyzed with a Hydrolab multiprobe and by the Environmental Research Institute; samples were collected or measured at 1-m subsurface from Connecticut water bodies, 1995 (TDP=total dissolved phosphorus; ALK=alkalinity; DOC=dissolved organic carbon; TSS=total suspended solids; PP=particulate phosphorus; PC=particulate carbon; PN=particulate nitrogen; Ca=calcium; Mg=magnesium).

Location	TDP mg/L	ALK mg/L	DOC mg/L	TSS mg/L	PP mg/L	PC mg/L	PN mg/L	Ca µg/L	Mg µg/L
Lake Qussapaug	-	-	-	-	-	-	-	2822	1315
Rainbow Reservoir	0.118	29	10.2	7.0	0.064	1.511	0.304	9216	2155
Rogers Lake	0.022	9	6.8	5.0	0.006	0.764	0.228	3237	1260
Lake Saltonstall	0.007	65	20.2	16.0	0.027	0.953	0.022	25320	8198
Saugatuck Reservoir	0.021	26	11.9	275.0	0.280	6.802	0.593	13030	4911
Silver Lake	0.028	64	24.4	3.0	0.025	1.294	0.343	22927	8284
Taunton Lake	0.043	28	12.2	13.0	0.037	3.656	0.495	10179	3636
Tyler Lake	0.026	43	17.2	0.5	0.026	1.754	0.261	11640	5345
Union Pond	0.234	52	17.8	7.0	0.123	1.372	0.197	19567	4484
Lake Waramaug	0.020	30	11.6	5.0	0.042	1.872	0.457	8135	3384
Wauregan Reservoir	0.004	7	5.7	0.5	0.015	0.659	0.038	5613	1407
Lake Winchester	0.024	6	17.4	0.5	0.011	0.888	0.079	2989	1254
Wonoskopomuc	0.028	103	33.6	0.5	0.023	0.994	0.104	23526	16477
Wyassup Lake	0.009	9	6.1	3.0	0.005	0.548	0.071	2950	988
Lake Zoar	0.041	57	20.1	20.0	0.025	0.972	0.162	15510	6239