Occurrence of Diatoms in Lakeside Wells in Northern New Jersey as an Indicator of the Effect of Surface Water on Ground-Water Quality

By Timothy J. Reilly, Christopher E. Walker, Arthur L. Baehr, Robin M. Schrock,
and John R. Reinfelder

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Conversion Factors, Vertical and Horizontal Datum

SI/ to Inch Pound

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
micrometer (m)	3.937x10^{-5}	inch (in.)
Area		
square kilometer (km^2)	247.1	acre
Volume		
liter (L)	0.2642	gallon (gal)
milliliter (mL)	0.0338	ounce, fluid (fl. oz)
Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)
milligram (mg)	3.53x10^{-5}	ounce, avoirdupois (oz)
microgram (μg)	3.53x10^{-5}	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or in micrograms per liter (μg/L).

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Abstract

In a novel approach for detecting ground-water/surface-water interaction, diatoms were used as an indicator that surface water affects ground-water quality in lakeside communities in northern New Jersey. The presence of diatoms, which are abundant in lakes, in adjacent domestic wells demonstrated that ground water in these lakeside communities was under the direct influence of surface water. Entire diatom frustules were present in 17 of 18 water samples collected in August 1999 from domestic wells in communities surrounding Cranberry Lake and Lake Lackawanna. Diatoms in water from the wells were of the same genus as those found in the lakes. The presence of diatoms in the wells, together with the fact that most static and stressed water levels in wells were below the elevation of the lake surfaces, indicates that ground-water/surface-water interaction is likely. Ground-water/surface-water interaction also probably accounts for the previously documented near-ubiquitous presence of methyl tertiary-butyl ether in the ground-water samples.

Recreational use of lakes for motor boating and swimming, the application of herbicides for aquatic weed control, runoff from septic systems and roadways, and the presence of waterfowl all introduce contaminants to the lake. Samples from 4 of the 18 wells contained *Navicula spp*., a documented significant predictor of *Giardia* and *Cryptosporidium*. Because private well owners in New Jersey generally are not required to regularly monitor their wells, and tests conducted by public-water suppliers may not be sensitive to indicators of ground-water/surface-water interaction, these contaminants may remain undetected. The presence of diatoms in wells in similar settings can warn of lake/well interactions in the absence of other indicators.

Introduction

Ground water generally is perceived as being less susceptible to the effects of human activities than surface water because of the protection afforded by filtering in the subsurface. Wells, however, can induce flow from surface water, which can result in inadequate removal and inactivation of pathogens through subsurface processes. The ground-water supply, therefore, may be vulnerable to contamination by *Giardia lamblia, Cryptosporidium parvuam, Cryptosporidium hominis*, and viruses from septic tanks and sewage-treatment facilities that discharge, directly or indirectly, to surface water that could reach the wells. Because routine ground-water analysis typically does not include testing for these pathogens, the undetected interaction of ground water and surface water, for some wells in some localities, can be undesirable.

The Surface Water Treatment Rule defines ground water under the direct influence of surface water (GWUDI) as "any water beneath the surface of the ground with significant occurrence of insects or other macroorganisms, algae, or large diameter pathogens such as *Giardia lamblia*. The criteria also include significant and relatively rapid shifts in water characteristics, such as turbidity, temperature, conductivity or pH, which closely correlate to climatological or surface water conditions" (U.S. Environmental Protection Agency, 1989). This regulation allows each state to determine which production wells, springs, and infiltration galleries are GWUDI; that is, the ground water can be regulated as if it were surface water. Direct influence can be determined by water-quality testing and (or) documentation of well construction and local geology (U.S. Environmental Protection Agency, 1990). Screening criteria for the determination of direct influence include characteristics such as the proximity of the well to a surface-water body, the depth and integrity of surface casing, the history of microbial contamination of the water in the well, and the results of microscopic particulate analysis (MPA) (Vasconcelos and Harris, 1992). Ground-water supplies determined to be under the direct influence of a surface-water body are subject to surface-water-treatment rules. Current (2005) regulation mandates disinfection and requires filtration of surface water or ground water under the direct influence of surface water unless protected by a watershed-control program or treated by alternatives to conventional filtration treatment methods such as bag or cartridge filters or in situ bank filtration (U.S. Environmental Protection Agency, 2002). These regulations apply to all public-water-supply systems; private (domestic) wells are not governed by these regulations.

The use of motorcraft, swimming, the application of herbicides for control of aquatic weeds and algae, runoff from surface breakouts from failing septic systems together with indirect discharge from operating systems, runoff from roadways, the presence of waterfowl, and many other factors can affect lake-water quality. The magnitude and duration of the effects of these factors are seasonal or sporadic and may not affect all parts of the lake equally. In humid settings, ground water generally discharges to lakes; however, lake levels commonly are maintained with impoundments that can cause the local water table to rise permanently (Winter and others, 1998). The impoundment of surface water, combined with the pumping of wells to supply water to lakeside communities, can reverse the natural direction of ground-water flow and cause ground water to receive recharge from the lake (Baehr and Reilly, 2001). In New Jersey, private-well owners generally are not required to monitor the quality of their water supply, and tests conducted by public-water suppliers in accordance with the Safe Drinking Water Act (U.S. House of Representatives, 2005) may not be sensitive to indicators of ground-water/surface-water interaction. Human exposure to undetected contaminants originating from wells that receive lake-water recharge with shorter than average travel times could occur in this setting.

Diatoms are a diverse group (about 10,000 living species) of photosynthetic autotrophic protists (Curtis and Barnes, 1989). Diatoms, which are abundant in most aquatic environments and live throughout the water column, use silica to form a rigid cell wall (frustule) (Prothero, 1998). When the diatoms die, frustules settle and can be preserved within lake-bottom sediments. Diatoms typical of Cranberry Lake range in shape and size from the pennate *Fragilaria crotonensis* Kitton (lmaj = 40-170 mm; lmin= 2-4 mm) to the centric *Cyclotella pseudostelligera* Hustedt (4-10 mm diameter) (table 1). The concentrations and relative abundances of diatom species differ by season and from year to year. Living diatoms are important ecological indicators, and frustules found in aquatic sediments commonly are used by geologists in biostratigraphic and paleoclimate analyses. Because diatoms require light to survive, their presence in ground water is indicative of a connection between ground water and surface water capable of rapidly transporting diatom-sized particles. The presence of diatom frustules of the same species in both lake and ground water is indicative of a lake/well interaction.

Ground-water ecologists have contributed much to the understanding of the biota within the hyporheic zone (Gibert and others, 1994; American Water Resources Association, 1994) and the development of biological tracers of ground-water/surface-water interaction (U.S. Environmental Protection Agency, 1998). Although many studies have documented

Table 1. Size, shape, and habitats for selected diatom species found in water samples from Cranberry Lake, northern New Jersey.

[axis length and shape from Krammer and Lange-Bertalot (1986, 1988, 1991a and b, 2000); habitat from Wetzel (1983) and Steveson and others (1996); μm, micrometer; --, no minor axis]

Species	Axis length (µm) Major	Axis length (µm) Minor	Shape	Habitat
Fragilaria crotonensis Kitton	40-170	2-4	pennate	planktonic, meso- to eutrophic
Aulacoseira granulata Ehrenberg	4-30	--	centric	planktonic, eutrophic
Asterionella formosa Hassall	40-80	1.3-6	pennate	planktonic, meso- to eutrophic
Cyclotella pseudostelligera Hustedt	4-10	--	centric	planktonic, eutrophic
Nitzschia palea Kützing	15-70	2.5-5	pennate	benthic or planktonic, eutrophic

the presence of biological material in ground-water samples, few have investigated algal taxa. Vasconcelos and Harris (1992) used diatoms and other microscopic organisms as indicators of ground-water/surface-water interaction in their MPA methodology, but no environmental case studies in which diatoms were specifically enumerated in ground-water samples have been reported. Moulton-Hancock and others (2000) conducted MPAs of 383 ground-water samples from 166 sites and found significant co-occurrence of diatoms (*Navicula* and *Synedra*) with *Giardia* and *Cryptosporidium*. Breakthrough of diatoms also has been reported in wells associated with riverbank filtration sites in Kearny, Nebraska (Schijven and others, 2003), and co-occurs with *Giardia* and *Cryptosporidium* in Loveland, Colorado (Berger, 2002).

During summer 1998, the U.S. Geological Survey (USGS) sampled four lakes in Byram Township, New Jersey, for methyl tertiary-butyl ether (MTBE) and other volatile organic compounds (VOCs). Concentrations of MTBE in samples collected from Cranberry Lake (fig. 1) ranged from 1.6 to 15.0 mg/L on June 24, and from 7.4 to 29.0 mg/L on September 8. Concentrations of MTBE in samples collected from Lake Lackawanna on September 9, 1998, ranged from 3.7 to 14.0 mg/L. The MTBE occurrence in the lakes was attributed to gasoline-powered watercraft (Baehr and Zapecza, 1998; Baehr and Reilly, 2001). These concentrations of MTBE in Cranberry Lake and Lake Lackawanna are among the highest observed nationwide in ambient surface-water samples collected to date (2005) by the USGS (Baehr and Reilly, 2001).

The high MTBE concentrations, together with the potential for lake/well interaction in this hydrologic setting, led the USGS to sample wells in the lakeside communities to assess ambient ground-water quality. At Cranberry Lake, 14 domestic wells were sampled in fall 1998 and again in August 1999. At Lake Lackawanna, five domestic wells were sampled in August 1999 only. MTBE was detected in samples from 18 of 19 wells. These results indicated that ground-water/surface-water interaction could be a potential source of the MTBE observed in local wells (Baehr and Reilly, 2001). Subsequently, the USGS, as part of the Toxic Substances Hydrology Program, conducted the current study to determine whether diatoms could be used as a tracer to verify that the lake was the source of MTBE in the wells.

This report describes the occurrence of substantial concentrations of diatoms in water samples collected concurrently from the wells. A modification to the MPA is described that allowed samples from domestic, rather than production, wells to be analyzed in order to verify that the ground water was under the influence of surface water and that the lake was the source of MTBE found in the local wells.

Study Area

Cranberry Lake and Lake Lackawanna are in Byram Township, Sussex County, New Jersey. The study area is in the New England physiographic province (fig. 1). The density and size of the lakes in New Jersey are greater north of the Wisconsinan terminal moraine than south of it; north of the moraine, the results of erosion and deposition associated with the Wisconsin glaciation, combined with topographic features, provide conditions favorable for lake enlargement with dams (Baehr and Reilly, 2001). The structural geology of the region is dominated by a series of northeast-southwest-trending faults and folds. Lake Lackawanna is underlain by unconsolidated glacial sediments, which in turn are underlain by fractured bedrock; Cranberry Lake is underlain entirely by fractured bedrock (Volkert and others, 1989). The bedrock consists of crystalline metamorphosed sedimentary and igneous rocks of Precambrian age. Bedrock outcrops in the study area have many near-vertical joint sets that may persist at depth.

Cranberry Lake (originally known as Cranberry Bog, then Cranberry Reservoir) was created by impoundment in the 1830's to provide water to the nearby Morris Canal (no longer in use). Recreational use of the lake increased in the 1920's with the construction of its current system of two dams, which resulted in its current surface area of about 0.77 km^2. The lake has an estimated volume of 1.5 x 109 L and an average depth of about 2 m. At present (2005), approximately 500 houses surround Cranberry Lake; about 75 percent of the houses are used as year-round residences. Lake Lackawanna (0.47 km^2) was created in 1910 by the damming of Lubbers Run. The lake has an estimated volume of 3 x 108 L and an average depth of 1.5 m. Lake Lackawanna is now surrounded by 300 houses, essentially all of which are used as year-round residences. Public access to Cranberry Lake results in heavier boat traffic and shoreline recreation use than that observed at Lake Lackawanna (Byram Township Environmental Commission, 1994).

Ground water is the primary source of water supply for the residents in the vicinity of Cranberry Lake and Lake Lackawanna. At Cranberry Lake, four small public-water suppliers serve approximately 160 residences; the remaining 340 residences derive their water from domestic wells (Baehr and Zapecza, 1998). At Cranberry Lake, wells typically are constructed with 15 m of surface casing and an open borehole through the fractured-rock aquifer. Lake Lackawanna residents rely entirely on domestic wells for their water supply. Some wells at Lake Lackawanna are drive points that tap unconfined glacial sediments; those that tap the fractured-rock aquifer are constructed similarly to those at Cranberry Lake. At both communities, the prevalence of near-vertical fractures at the surface, the presence of thin (generally less than 3-m thick) soils, and the close proximity of wells to the lakes indicates that vulnerability to surface contamination is likely.

Methods of Study

To determine the hydraulic gradient near each well, lake stage and ground-water altitudes were determined by land survey with an autolevel (third-order accuracies), and locations were determined using a Garmin handheld global positioning system receiver. The location of each well was validated using

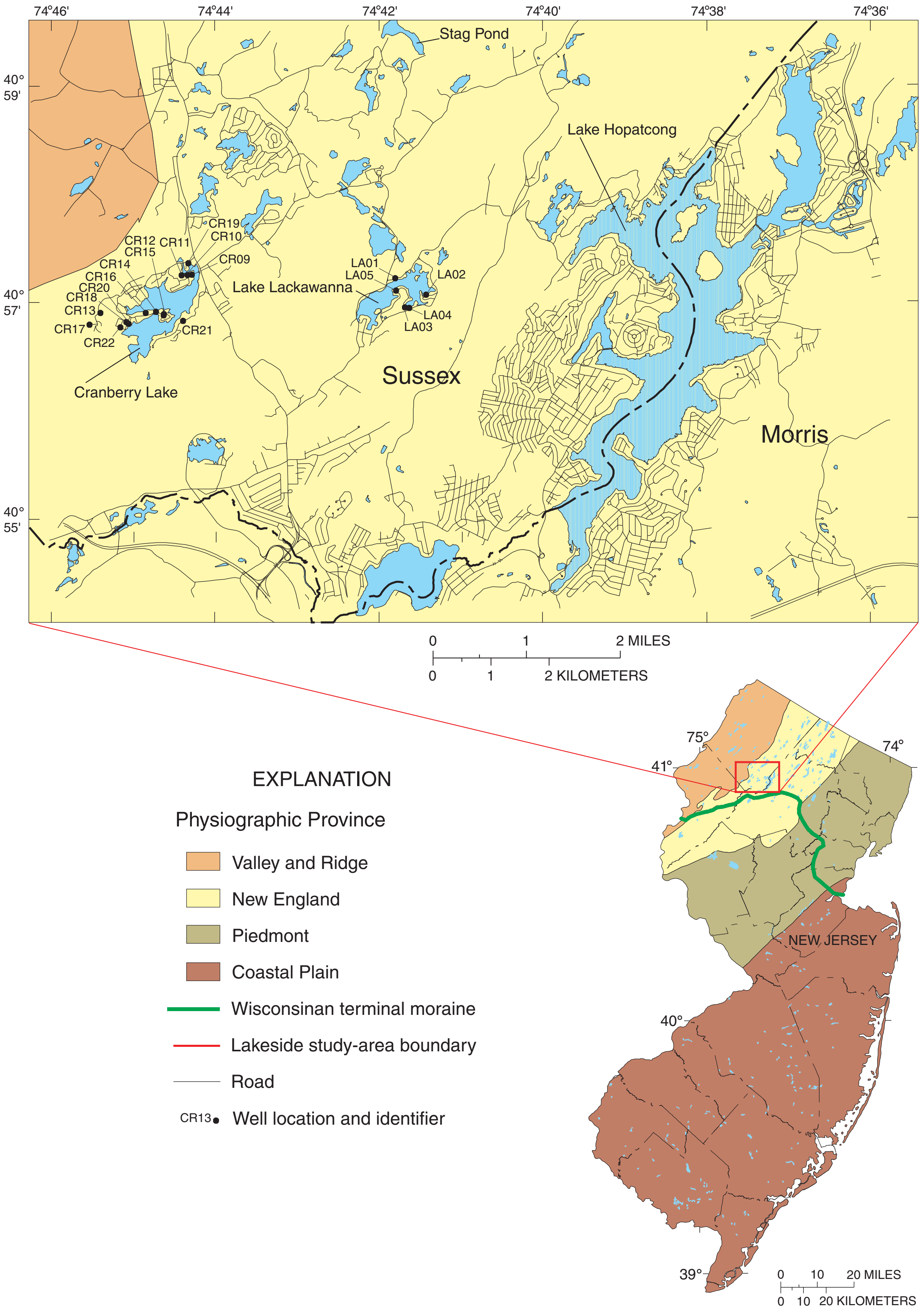

Figure 1. Location of study area, lakes, and physiographic provinces in northwestern New Jersey.

1-m-resolution digital orthophoto quadrangles. Static water levels were measured in the wells after a period of inactivity (2-24 hours). Under this condition, the domestic wells serve as observation wells. Stressed water levels, which are the lowest water levels observed during sampling and are representative of the water levels in the wells during pumping, also were measured. Water levels in wells were measured twice with a steel tape.

Samples from Cranberry Lake were collected with a peristaltic pump and polyethylene tubing from 0.9 m below the lake surface. Ground-water samples were collected with the well owner's submersible pump and disposable, Teflon-lined polyethylene tubing as described in Baehr and Reilly (2001). Two 1-L polyethylene bottles of unfiltered water were collected to determine the diatom concentration, preserved with 10 mL of a 37-percent formaldehyde solution, and immediately chilled to 4 °C. Three 40-mL amber vials of unfiltered water were collected to determine VOC concentrations (including MTBE), preserved to pH less than 2 with hydrochloric acid, and immediately chilled to 4 °C. Samples to be analyzed for VOCs were shipped overnight to the USGS National Water-Quality Laboratory in Arvada, Colo., and analyzed by purge-and-trap gas chromatography/mass spectrometry (GC/MS) methods (Connor and others, 1997).

Samples were prepared for microscopic analysis by filtering 400 mL of unfiltered sample through a 0.45-mm mixed cellulose ester filter. The filter was digested with concentrated sulfuric acid and repeatedly rinsed with deionized water until the pH was approximately neutral (7 standard units). The sample was centrifuged, and the supernatant was removed to concentrate the sample to 1 to 2 mL. A 0.5-mL subsample then was mounted on a slide using Naphrax high-resolution mounting medium for examination. Diatoms were identified and photographed under 1,000x magnification using a Nikon Eclipse E600 microscope with an oil immersion lens under phase contrast illumination. Patrick and Reimer (1966, 1975) and Krammer and Lange-Bertalot (1986, 1988, 1991a, 1991b, 2000) were used as primary references for diatom taxonomy. The whole area of the coverslip was examined under phase contrast illumination at 200x and 400x magnification to count cells and avoid bias (Battarbee and Kneen, 1982). Concentrations were estimated by dividing the number of observed cells by the percentage of the sample examined. This procedure resulted in the examination of 10 to 20 percent of the raw-water sample. A statistical analysis using Spearman's rho was conducted to determine correlations between diatom concentration and distance from the well to the lake, static and stressed ground-water levels, well-casing depth, length of open interval, and MTBE concentration.

Occurrence of diatoms in lakeside wells

Water samples collected from Cranberry Lake contained a variety of phytoplankton, including diatoms of the genera *Aulacoseira, Cyclotella, Synedra, Pinnularia, Navicula, Gomphonema, Cymbella, Asterionella, and Fragilaria*. The cell counts of diatoms in Cranberry Lake in July 1999 were about 2 to 4 x 105 cells L^{-1}. Whole (intact) diatom frustules were found in water from nearly all sampled wells (13 of 14 wells at Cranberry Lake and 4 of 4 wells at Lake Lackawanna) (table 2).

Frustules were present in samples from wells completed in both fractured-rock and unconsolidated glacial-sediment aquifers. The cell counts of diatoms in ground-water samples ranged from 0 to 687 cells L^{-1}; the median count was 128 cells L^{-1}. Frustules identifiable to the genus level were observed in all ground-water samples containing diatom remains. Most of the observed frustules were consistent with the morphology of *Aulacoseira*. Similar frustules were observed in samples from Cranberry Lake.

Static water levels were measured in 17 wells; 12 of the 17 static water levels were lower than the lake-surface elevation (table 3, figs. 2A and 3A). Static ground-water levels below lake level indicate local movement of water from the lake into the aquifer. Stressed water levels also were measured in 13 wells; 12 of the 13 stressed water levels were lower than the lake-surface elevation (figs. 2B and 3B). Water levels lower than the lake surface indicate that some of the water entering the wells is derived from the lake.

The presence of MTBE in ambient ground water underlying the study area has been documented previously (Baehr and Reilly, 2001). MTBE was detected in 18 (94.7 percent) of the 19 sampled wells. Concentrations ranged from non-detectable to 13.2 mg/L; the median concentration was 0.24 mg/L. MTBE was the dominant VOC (in both concentration and frequency of occurrence) in samples from the selected wells.

The detection of diatom frustules in nearly every sampled well, and the identification of diatoms of the same genera in lake water and ground water, provide strong evidence that surface water is leaking into the aquifers surrounding these lakes. Wells with static water levels below the lake stage (71 percent of sampled wells) receive water from the lake. Nearly every well in which stressed water levels were measured (92 percent of sampled wells) draws water from the lake when pumped. Diatoms were present in three wells in the fractured-rock aquifer (CR13, CR17, and CR22; table 2) that are relatively distant from the lake (less than 0.1 km from the shore). Two of these wells (CR17 and CR22) had water levels higher than the lake elevation. It is possible that the lake is the source of diatoms to these wells. Wells in a fractured-rock aquifer can receive recharge at differing rates from multiple fractures along the open interval of the well. The well could intersect a fracture network connected to the lake while also drawing in water from upgradient recharge areas through other fractures. This scenario could cause the well to be vulnerable to contamination from the lake although the water level in the well is higher than the lake elevation.

It was anticipated that diatom concentration would be inversely related to distance from the well to the lake, static and stressed ground-water levels, well-casing depth, length of open interval, and MTBE concentration. Correlations between

Table 2. Number and species of diatoms in water samples from domestic wells near Cranberry Lake and Lake Lackawanna, northern New Jersey.

[L, liters]

Well number (figs. 2 and 3)	Total diatom concentration (cells/L)	Species present (cells/L)
		Cranberry Lake
CR09	0	None present
CR10	219	*A. granulata* (66), *F. crotonensis* (55), *F. capucina* (44), *Navicula* spp. (33), *Achnanthes* spp. (11), *Cymbella* spp. (11)
CR11	50	*F. crotonensis* (40), *Synedra spp*. (10)
CR12	22	*F. crotonensis* (22)
CR13	57	*A. granulata* (57)
CR14	687	*A. granulata* (687)
CR15	124	*F. crotonensis* (83), *A. granulata* (41)
CR16	393	*A. granulata* (197), *C. pseudostelligera* (98), *Achnanthes* spp. (20), *C. placentula* (20), *F. crotonensis* (20), unknown (38)
CR17	128	*A. formosa* (128)
CR18	20	*Cyclotella* spp. (20)
CR19	87	*A. granulata* (70), *Pinnularia* spp. (17)
CR20	149	*A. granulata* (149)
CR21	131	*A. granulata* (87), *A. formosa* (22), *Navicula* spp. (22)
CR22	201	*A. granulata (90), F. crotonensis* (67), F. capucina (22), C. placentula (22)
		Lake Lackawanna
LA02	126	*A. granulata (54), F. crotonensis* (54), *Achnanthes* spp. (18)
LA03	116	*A. granulata* (99), *Navicula* spp. (17)
LA04	62	*A. granulata* (62)
LA05	32	*F. crotonensis* (32)

these variables were determined using Spearman's rho (table 4).

No significant relations ($p<0.05$) were observed between diatom concentration and any of the other variables. The only significant relation observed was a negative correlation between MTBE concentration and well-casing depth. This result is not surprising as shorter well casings generally allow recharge with younger water traveling along shallower flow paths than do longer well casings (MTBE concentration typically is time-dependent, as it is subject to degradation by volatization and microbial respiration.) A possible explanation for the lack of statistical relations with the other causal factors is that the precision of the diatom concentration determination was not sufficient for this analysis.

Most experimental and ecological observations are concerned with a 100-percent change in abundance so that a counting technique with an accuracy of +/- 50 percent of the true value is adequate (Wetzel and Likens, 2000). On the basis of the counting technique described above, a random distribution of diatoms on the slide was assumed (Battarbee and Kneen, 1982). Counting errors were calculated for each measurement using a Poisson distribution (Lund and others, 1958). Although two of the samples had acceptable errors (CR-10, +58/-37 and CR-16, +58/-37), most of the cell counts had errors greater than +/- 50 percent. The lack of precision in the counting technique used in this study weakens the ability to relate diatom cell counts to other variables.

The lakes are not the only potential source of the diatoms and MTBE found in the surrounding wells. Diatoms are likely to inhabit other environments near the lake (including wetlands, streams, and puddles) and may be present in soils. The layer of sediment that has accumulated on the bottom of lakes probably also contains an abundance of diatom remains. If the diatoms traveled from a source other than the lake to these wells, they would have traveled a vertical distance at least as long as the cased intervals of the wells (15.2-39.6 m), which in many cases is similar to the distance from the lake to the well.

Table 3. Physical characteristics of, water levels and methyl tert-butyl ether (MTBE) concentrations in, and distances from Cranberry Lake and Lake Lackawanna in northern New Jersey to, wells sampled during August 1999.

[FB, fractured bedrock; UGS, unconsolidated glacial sediments; water levels are in meters above the elevation of lake during survey (Cranberry Lake = 770.1 meters; Lake Lackawanna = 717.75 meters); NR, no record; DP, drive point; --, not measured; ND, not detected; m, meters]

Well number (figs. 2 and 3)	Aquifer material	Cased depth (m)	Uncased interval (m)	Distance to lake (m)	Static water level (m)	Stressed water level (m)	MTBE (μg/L)
Cranberry Lake							
CR09	FB	15.2	77.7	45.7	1.52	--	3.33
CR10	FB	NR	NR	18.2	3.15	--	.38
CR11	FB	NR	NR	19.1	-4.26	-18.10	.62
CR12	FB	NR	NR	24.9	-1.95	--	13.24
CR13	FB	25.9	35.1	450.4	--	--	.2
CR14	FB	15.8	37.5	12.1	-.62	-26.07	ND
CR15	FB	15.5	7.3	69.0	-.14	-.79	.24
CR16	FB	15.2	38.1	35.6	-1.28	-3.35	.32
CR17	FB	15.5	98.8	673.4	9.68	7.27	.14
CR18	FB	15.2	14.9	83.5	-.1	-1.82	.5
CR19	FB	15.2	7.6	8.1	-.02	-5.78	.41
CR20	FB	25.9	34.4	61.0	-.3	-.65	.3
CR21	FB	31.7	127.7	80.9	-2.86	-29.19	.23
CR22	FB	15.2	29.9	104.0	.16	-.96	3.59
Lake Lackawanna							
LA01	FB	15.2	29.3	27.3	-.16	-2.52	.08
LA02	UGS	15.2	DP	7.4	-.16	-.21	.07
LA03	FB	35.1	25.9	7.1	1.14	-4.22	.19
LA04	UGS	29.6	DP	10.9	--	--	ND
LA05	FB	39.6	21.3	39.4	-.27	--	.05

MTBE is a commonly occurring contaminant in domestic wells in the New England (47 percent; n=30) and Piedmont (36 percent; n=22) physiographic provinces of New Jersey (Ayers and others, 2000). In this study MTBE was nearly ubiquitous (frequency of detection 93 percent; n=19), and median concentrations of MTBE were significantly higher than other surveys of domestic wells in the same physiographic setting (Baehr and Reilly, 2001). MTBE is used throughout the country as a fuel additive and can be associated with runoff from roads, leaking fuel tanks, and vehicle emissions; however, previous investigations in the area found no reports of leaking fuel tanks (Baehr and Zapecza, 1998).

Geologic setting may be an important control on the vulnerability of wells to the effects of surface water and the occurrence of surface-water diatoms in water from wells. In this study, only 2 of 19 sampled wells were constructed in unconsolidated glacial sediments, which is not a sufficient sampling to test aquifer material as a variable. On the basis of the sizes of diatoms present in the wells (table 1), pathways in both unconsolidated glacial sediments and fractured rock must be capable of transporting a particle with a minimum short axis length of 1.2 mm. The porosity and grain size are not known for either of these aquifer materials. Coring of the unconsolidated glacial sediments and caliper logging of wells constructed in the fractured-rock aquifer would help in determining the physical mechanisms of diatom transport. Alternatively, as in a recent study, proteins associated with diatoms (rather than the entire diatom itself) could be used to detect wells under the influence of lakes (Walker and others, 2005).

The sample-collection and analysis methods used in this study differ from the U.S. Environmental Protection Agency consensus method for MPA (Vasconcelos and Harris, 1992). The consensus method was designed to monitor public-water supplies and calls for an 8- to 24-hour sampling period during

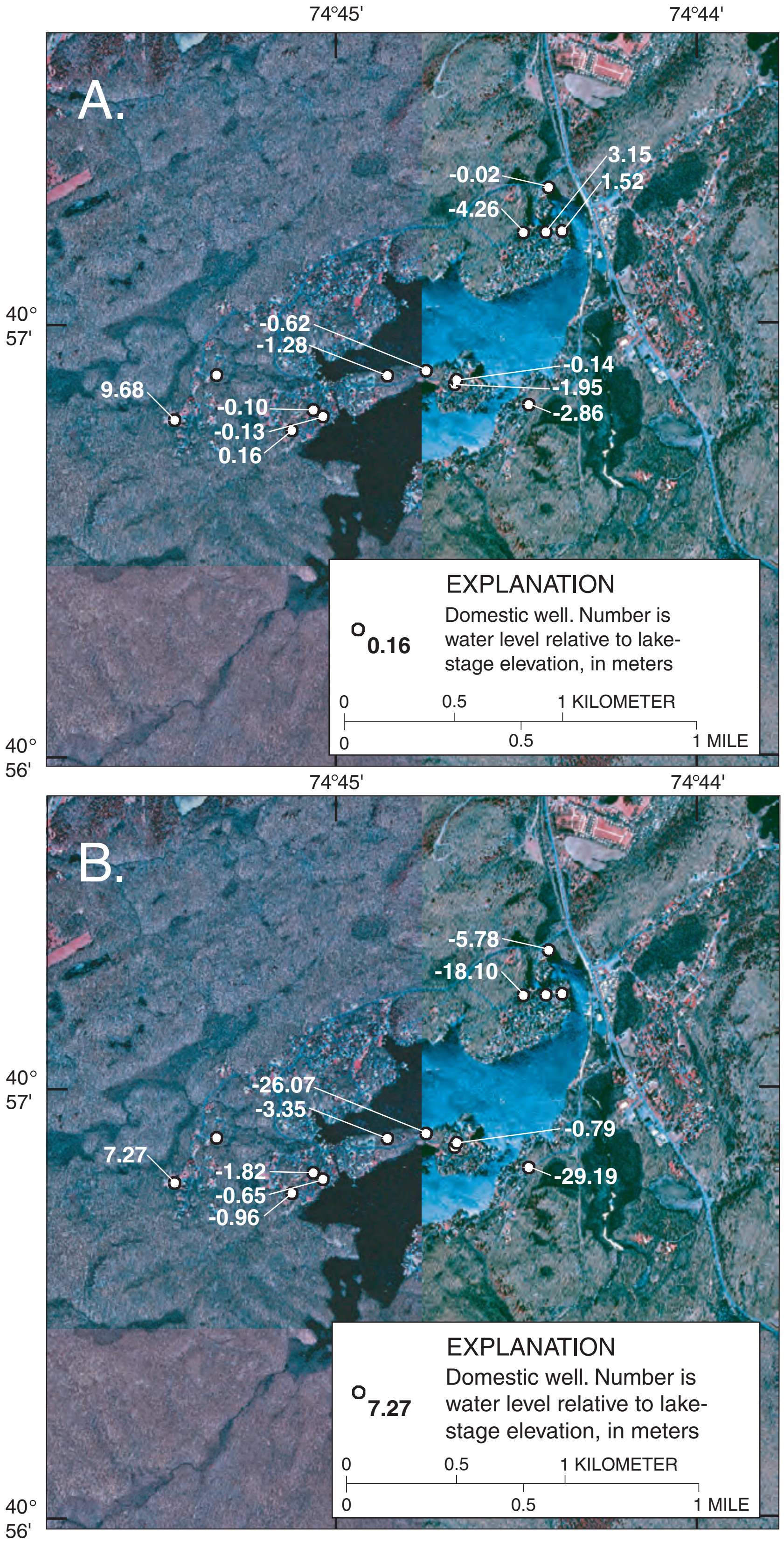

Figure 2. (A) Static and (B) stressed water levels in domestic wells near Cranberry Lake, northern New Jersey, relative to lake-stage elevation of 234.7 meters above NAVD 88, August 1999.

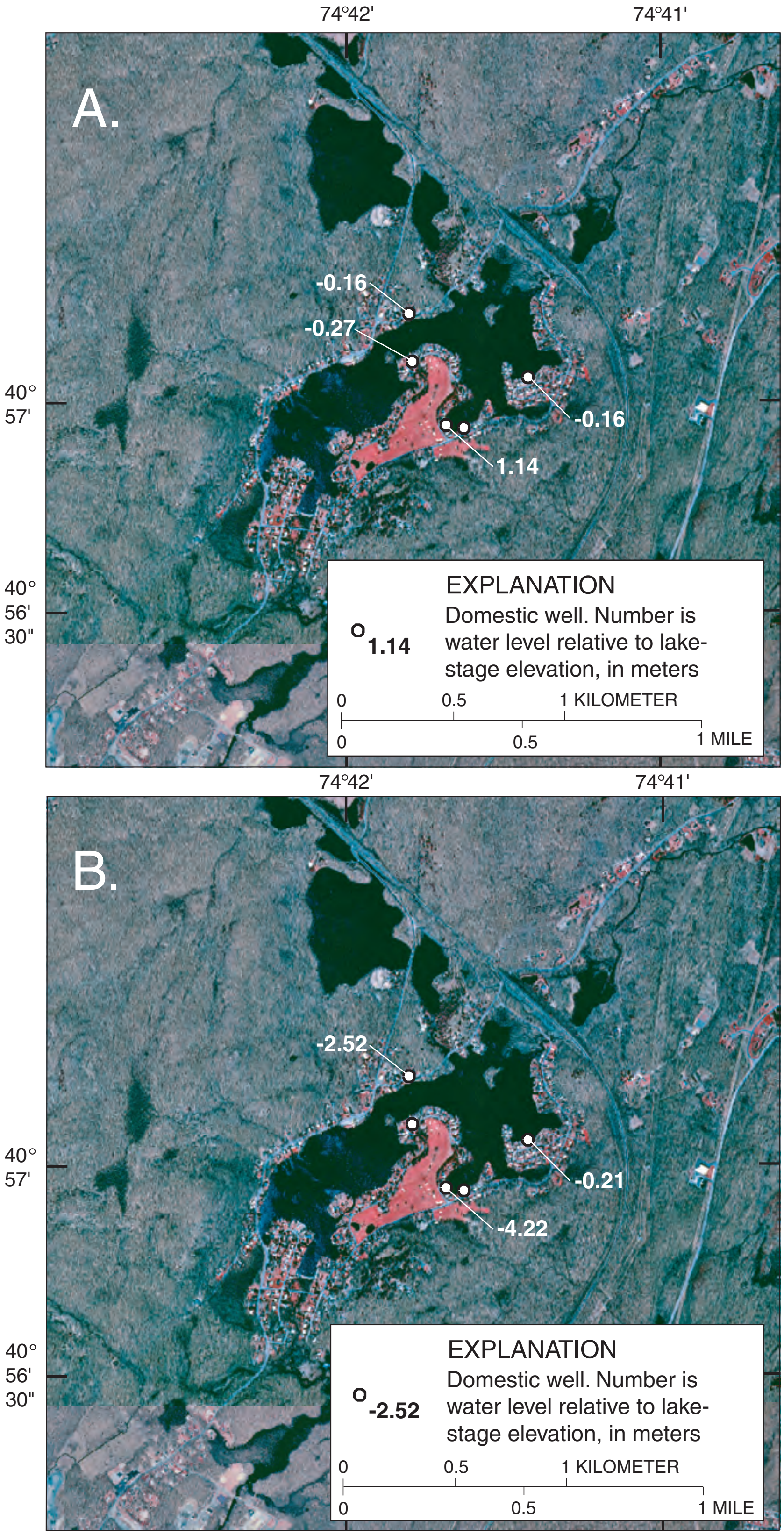

Figure 3. (A) Static and (B) stressed water levels in domestic wells near Lake Lackawanna, northern New Jersey, relative to lake-stage elevation of 218.7 meters above NAVD 88, August 1999.

Table 4. Correlations between diatom concentrations and selected well-construction characteristics, well location, static and stressed water levels, and concentrations of methyl tertiary-butyl ether (MTBE) for wells near Cranberry Lake and Lake Lackawanna, northern New Jersey.

[m, meters; µg/L, micrograms per liter; L, liters]

Spearman's rho	Well casing depth (m)	Uncased interval (m)	Distance to lake (m)	Static water level (m)	Stressed water level (m)	MTBE (µg/L)	Total diatom concentrtion (cells/L)
Well casing depth (m)	1						
Uncased interval (m)	.084	1					
Distance to lake (m)	-.031	.297	1				
Static water level (m)	-.202	-.077	.154	1			
Stressed water level (m)	-.243	-.127	.351	.531	1		
MTBE (µg/l)	-.529	-.090	.239	.094	-.077	1	
Total diatom concentration (cells/L)	-.068	.313	-.051	-.012	.007	-.268	1

Probability	Well casing depth (m)	Uncased interval (m)	Distance to lake (m)	Static water level (m)	Stressed water level (m)	MTBE (µg/L)	Total diatom concentrtion (cells/L)
Well casing depth (m)	1						
Uncased interval (m)	.766	1					
Distance to lake (m)	.901	.288	1				
Static water level (m)	.461	.783	.540	1			
Stressed water level (m)	.414	.677	.227	.067	1		
MTBE (µg/l)	.040	.740	.311	.709	.783	1	
Total diatom concentration (cells/l)	.793	.282	.832	.959	.991	.266	1

which 1,890 to 3,785 L of ground water are filtered. The wells sampled during this study are small-diameter (typically 4-in.) domestic wells in which it was not practical to operate the owner's submersible pump for such a long sampling period. The MPA concentrates material from a much larger sample volume than the method used here. Therefore, cell counts resulting from a MPA may be more accurate than results of a particle analysis conducted on a smaller volume of sample; however, the method used in this study is less intrusive for homeowners and allows for ambient surveys using domestic wells, not only production wells.

Summary and Conclusions

Substantial concentrations of diatoms, which are abundant in lakes, were found in water samples collected concurrently from lakeside wells in northern New Jersey. The presence of diatoms in the wells indicates that the ground-water supply may be vulnerable to contamination by various pathogens and viruses that are directly or indirectly discharged to surface water that could reach wells in the area. Results of previous work showed that ground-water/surface-water interaction could be a potential source of methyl tertiary-butyl ether (MTBE) observed in local wells. Therefore, the U.S. Geological Survey, as part of the Toxic Substances Hydrology Program, conducted this study to determine whether diatoms could be used as a tracer to verify that the lake was the source of MTBE in the wells.

To determine the hydraulic gradient near each well, lake stage and ground-water altitudes were determined by land survey and locations were determined using a global positioning system receiver. Water samples were collected from Cranberry Lake, Lake Lackawanna, and 18 lakeside domestic wells. Samples were analyzed using a modification of the U.S. Environmental Protection Agency's MPA technique in which a smaller volume of sample was used. Although cell counts resulting from a MPA may be more accurate than results of a particle analysis conducted on a smaller sample volume, the method used in this study is less intrusive for homeowners and allows for ambient surveys using domestic wells rather than only production wells.

The results of this study indicate that diatom frustules can be used as an indicator of ground-water/surface-water interaction. Whole diatoms were found in water samples from domestic wells constructed in both fractured-rock and unconsolidated glacial aquifers in lakeside communities in northern New Jersey, a setting prevalent in the northeastern United States. Samples from 13 of 14 wells near Cranberry Lake and 4 of 4 wells near Lake Lackawanna contained diatom frustules, including taxa that also were identified in samples of lake water. Selected wells in these lakeside communities also showed a high frequency of detection of MTBE in lakeside wells relative to other wells in the same geologic setting. This scenario is attributed to the movement of water from the lake to the wells. Hydraulic evidence from static- and stressed-water-level measurements also indicates that water moves from the lakes into the aquifer. Transport of diatoms from the lake to nearby wells could indicate that contaminants and pathogens from the surface are being introduced into local drinking-water supplies. Detection of *Navicula* in 4 of 18 samples is of particular interest because previous studies have shown that the presence of that diatom genus is a significant predictor of contamination with *Giardia* and *Cryptosporidium*. Because private well owners in New Jersey generally are not required to regularly monitor their wells, and tests conducted by public-water suppliers may not be sensitive to indicators of ground-water/surface-water interaction, these contaminants may remain undetected. The presence of diatoms in wells in similar settings can warn of lake/well interactions in the absence of other indicators.

Investigations of ground-water quality in additional lakeside communities would help in determining the regional ground-water vulnerability in this setting. Determination of the hydraulic properties of the aquifer materials would allow evaluation of geologic setting as a variable and determination of the flow path between lakes and wells.

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