USE OF AN ULTRA-CLEAN SAMPLING TECHNIQUE WITH INDUCTIVELY COUPLED PLASMA-MASS SPECTROMETRY TO DETERMINE TRACE-ELEMENT CONCENTRATIONS IN WATER FROM THE KIRKWOOD-COHANSEY AQUIFER SYSTEM, COASTAL PLAIN, NEW JERSEY

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square inch (in^2)	6.45	square centimeter
	Volume	
gallon (gal)	3.785	liter
	Mass	
ounce, avoirdupois (oz)	28.35	gram
pound, avoirdupois (lb)	0.4536	kilogram
	Temperature	
degree Fahrenheit (°F)	°C = 5/9 x (°F-32)	degree Celsius (°C)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Water-quality abbreviations:

L - Liter
mg/L - milligrams per liter
pCi/L - picocuries per liter
µS/cm - microsiemens per centimeter at 25 degrees Celsius
µg/L - micrograms per liter
mg/L - milligrams per liter
DO - dissolved oxygen

USE OF AN ULTRA-CLEAN SAMPLING TECHNIQUE WITH INDUCTIVELY COUPLED PLASMA-MASS SPECTROMETRY TO DETERMINE TRACE-ELEMENT CONCENTRATIONS IN WATER FROM THE KIRKWOOD-COHANSEY AQUIFER SYSTEM, COASTAL PLAIN, NEW JERSEY

By Tamara Ivahnenko, Zoltan Szabo, and Gene S. Hall

ABSTRACT

Water samples were collected during 1993 from 22 public supply wells screened in the Kirkwood-Cohansey aquifer system; concentrations of 18 trace elements were determined primarily by using inductively coupled plasma-mass spectrometry (ICP-MS) techniques, though graphite furnace atomic adsorption, hydride generation, and cold-vapor flameless atomic adsorption techniques were used for thallium, arsenic, and mercury, respectively, at the U.S. Geological Survey (USGS) National Water Quality Laboratory (NWQL). In addition, laboratory measurements of alkalinity and turbidity were made. The ground-water samples were collected by using ultra-clean sampling protocols developed by the USGS for collecting ground-water samples in areas with water containing low concentrations of trace elements. This technique is based on recently gained experience in sampling surface water for these elements. Field parameters (water temperature, specific conductance, pH, and dissolved-oxygen concentration) were monitored prior to sample collection. Three equipment blanks were collected to ensure that low-level trace-element contamination did not occur during sample collection. One split sample and a commercially-prepared reference standard were submitted to the NWQL to evaluate laboratory precision and accuracy, respectively. Trace-element concentrations in 10 sample splits and one equipment blank were also determined at the Rutgers University Chemistry Department laboratory.

Results of the ICP-MS analyses and cold vapor flameless atomic absorption indicated that five trace elements-- cobalt, copper, lead, mercury, and nickel--were detectable in low concentrations (<0.1-29 µg/L) in most of the samples from the 22 wells, and four elements--aluminum, barium, manganese and zinc--were detected in higher concentrations than the other elements (30-710 µg/L for aluminum; 4-180 µg/L for barium, manganese, and zinc). The remaining nine trace elements were present in concentrations consistently lower than the minimum reporting limit. Turbidity was low (less than 1 nephelometric turbidity unit (NTU)), indicating that the trace-element

concentrations were present in the dissolved phase and ideally would be reproducible in the absence of highly variable concentrations of particulates. The concentration of lead in one sample exceeded the U.S. Environmental Protection Agency (USEPA) action level of 15 µg/L; concentrations ranged from <1 to 16 µg/L. Mercury was frequently detected; concentrations ranged from <0.1 to 1.1 µg/L but did not exceed the USEPA maximum contaminant level.

Results of analyses of the equipment blanks indicated that samples collected by using the new ultra-clean sampling protocols were free of low-level (< 1µg/L) trace-element contamination. The analysis of the split sample sent to the NWQL had a difference of 5 percent or less for all constituents except aluminum, for which the analysis had a difference of 10 percent. Results of ICP-MS analyses of split water samples sent to the Rutgers University Chemistry Department laboratory were, in general, in good agreement (within 10 percent) with those of the NWQL. Results of the analysis of the commercial standard agreed (within 5 percent) with the known concentrations of the trace elements. The quality-assurance data (three blanks, one split sample, and one standard), although not statistically evaluated because of the small data set, indicate that the measured trace-element concentrations are precise and accurate and that the samples were free of contamination at the microgram-per-liter level of contamination.

INTRODUCTION

Accurate and precise analysis for trace elements in ground water at concentrations in micrograms per liter is necessary because large-scale dispersion of trace elements in the environment by human activity can lead to long-term degradation of ground-water quality. Human activities during the last 50 years have caused widespread changes in the distribution of trace elements in the environment. Large-scale increases in concentrations of lead (Chow and Earl, 1970) and mercury in the atmosphere (Swain and others, 1992) and lead in soils (Johnson and others, 1982) have been reported. The increase of these contaminants in air and soil could result in increased contamination of shallow, young ground water.

Chemical products widely dispersed through agricultural practices, road salting, and industrial practices have degraded the quality of ground water. Agricultural chemicals in recharge water filter through the aquifer system, resulting in the deterioration of the natural capacities of the aquifer matrix (sediment surfaces) to retard the mobility of many constituents, such as radium and trace elements. For example, high concentrations of radium in ground water have been found to correlate with greater-than-background concentrations of nitrate (Barringer and others, 1991). This pattern has been attributed to changes in ground-water quality due to leachates from fertilizer and soil additives (Kozinski and others, 1995).

The USEPA has recently mandated or proposed the lowering of maximum contamination limits or action levels of several trace elements (lead, mercury, thallium, cadmium, beryllium, and antimony) to 10 µg/L or less (U.S. Environmental Protection Agency, 1991). For most of these trace elements, dissolved concentrations less than 10 µg/L cannot be detected by the current, frequently used inductively coupled plasma-atomic emission spectroscopy (ICP-AES) "trace-element scans"; furthermore, improvement of sampling protocols is necessary to ensure the integrity of the sample.

The purpose of this study, conducted by the U.S. Geological Survey (USGS) in cooperation with the New Jersey Department of Environmental Protection (NJDEP), is to determine concentrations of trace elements with great accuracy at low levels (1 µg/L) through the use of the new analytical technique, inductively coupled plasma-mass spectrometry (ICP-MS). The USGS has developed ultra-clean sampling protocols for the collection of trace-element samples from surface water (Horowitz and others, 1994); these protocols were modified and applied to ground-water sampling to eliminate the possibility of sample contamination in the field. The new, highly sensitive analytical techniques together with the ultra-clean sampling protocols ensure the accuracy, precision, and improved representation of trace-element concentrations in ground water samples. Quantification of trace elements at the microgram-per-liter level, allows accurate establishment of a trace-element baseline to which future analyses can be compared. Shallow, young ground water commonly is used for drinking water and typically discharges to streams as baseflow. To develop stratagies to protect the quality of this resource, it is necessary to understand the spatial distribution of trace elements within the shallow aquifer systems and the water-quality changes through time.

Samples to be analyzed for low-level trace-elements were collected from public supply wells completed in the shallow, unconfined Kirkwood Cohansey aquifer system by using newly designed ultra-clean sampling protocols. Concentrations of trace elements were determined for samples collected in both agricultural and non-agricultural areas. The trace elements analyzed for are barium (Ba), beryllium (Be), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), manganese (Mn), molybdenum (Mo), nickel (Ni), silver (Ag), zinc (Zn), antimony (Sb), aluminum (Al), and uranium (U). In addition, the concentration of arsenic (As) was determined to the reporting level of 1 µg/L by use of hydride generation; thallium (Tl) was measured to 1 µg/L by graphite furnace atomic absorption; and mercury (Hg) was determined to 0.1 µg/L by cold-vapor atomic absorption. Accuracy and precision were monitored by the use of a commercially prepared reference standard and split samples that were analyzed at the USGS National Water Quality laboratory (NWQL) and the Rutgers University Chemistry Department laboratory (hereafter called the Rutgers laboratory).

Purpose and Scope

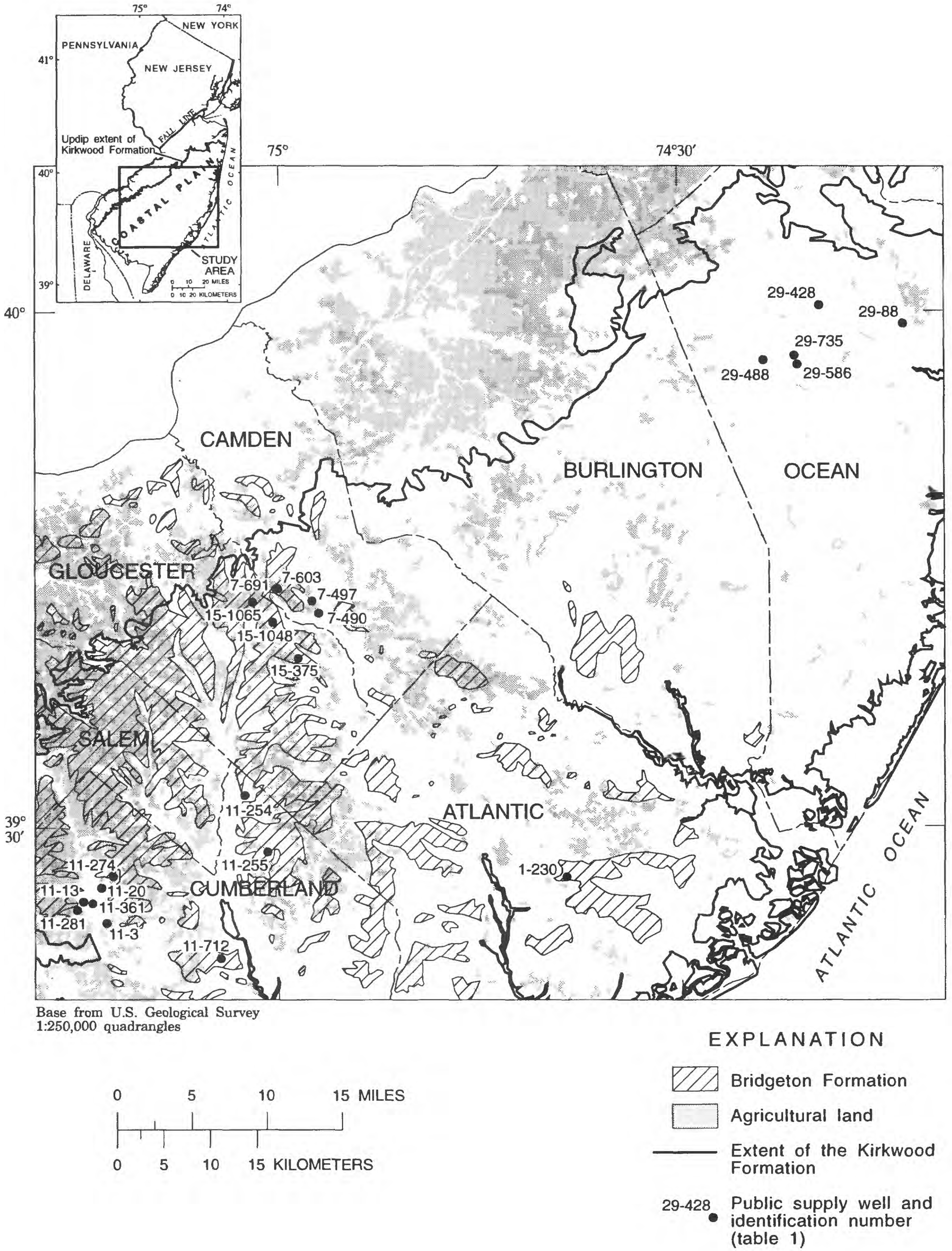
This report describes the modification of surface-water low-level trace-element sampling protocols of Horowitz and others (1994) to develop a sampling protocol for low-level trace-element sampling of production wells. This report also lists the concentrations of trace elements measured in water from 22 public supply wells screened in the Kirkwood-Cohansey aquifer system that were sampled using the new protocol. The minimum reporting limit is 0.1 for Hg and using ICP-MS is 1 μg/L for the concentrations of the following trace elements: Ba, Be, Cd, Cr, Co, Cu, Pb, Mn, Mo, Ni, Ag, Zn, Sb, Al, and U. Quality-assurance data which can be used to evaluate the degree to which sample contamination was minimized by the sampling protocol and laboratory performance are reported. Results of analyses performed at the USGS NWQL of three equipment blanks, one split sample, and one standard solution are included. Results of analyses performed at the Rutgers laboratory of 10 additional split samples and one equipment blank for concentrations of Ba, Cd, Cr, Cu, Pb, Mn, Ni, Zn, and Al and for the ratios of isotopes of lead are also included. Water-quality data for samples collected from 21 of the same wells during 1986-90, but analyzed with the ICP-AES technique, are presented for comparison.

Description of the Study Area

The study area encompasses most of the Kirkwood-Cohansey aquifer system (fig. 1), which is the major unconfined aquifer system in the Coastal Plain of New Jersey. It is the primary source of domestic and public drinking-water supply in most of the southwestern Coastal Plain. The study area includes parts of Atlantic, Camden, Cumberland, Gloucester, and Ocean Counties.

The Kirkwood-Cohansey aquifer system is composed of hydraulically connected sediments (predominantly fine- to medium-grained sand) of the Kirkwood Formation and the Cohansey Sand. Sands and gravels of the Bridgeton Formation locally overlie, and are in hydraulic connection with, the Cohansey Sand in southwestern New Jersey. The aquifer in southwestern New Jersey is thicker where erosional remnants of the Bridgeton Formation are present than where Bridgeton Formation deposits are absent. A thick, regionally extensive, diatomaceous marine clay, called the Alloway Clay in southwestern New Jersey, forms the basal part of the Kirkwood Formation and the basal boundary of the aquifer system (Zapecza, 1989). This formation crops out in the southwestern part of the State and marks the western boundary of the aquifer (fig. 1).

Topography is characterized by low altitude and relief, both of which decrease eastward from topographic highs (about 120 ft above sea level) in Gloucester County, southwestern New Jersey, to sea level at the Atlantic Ocean (Lacombe and Rosman,



Base from U.S. Geological Survey
1:250,000 quadrangles

Figure 1. Location of the outcrop of the Kirkwood Formation, the extent of the Kirkwood-Cohansey aquifer system, the extent of the Bridgeton Formation, agricultural land, and the public supply wells sampled, Coastal Plain, New Jersey.

1995). The Bridgeton Formation (fig. 1) crops out in topographically high areas (typically at and adjacent to the ground-water divide), and is overlain by well-drained acidic loamy, sandy, or gravelly soil that is widely used for agriculture. About 35 percent of the study area is agricultural land. The aquifer system is recharged by percolation of precipitation that falls directly on the aquifer system. Average annual precipitation in southwestern New Jersey is about 42.1 in. of which about 18.5 in. becomes ground-water recharge (Martin, in press; Lacombe and Rosman, 1995).

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METHODS OF INVESTIGATION

Sampling Network

Samples were collected during 1993 from 22 public supply wells screened in the Kirkwood-Cohansey aquifer system (fig. 1). These wells and one other well now sealed were sampled previously; samples were analyzed for radionuclides, major ions, nutrients, and trace elements. Well-construction data for these wells are provided in table 1. Analyses for trace-element concentrations in previously collected samples were performed by using the ICP-AES technique (Kozinski and others, 1995). Wells were selected in areas of agricultural land use (Atlantic, Camden, Cumberland, and Gloucester Counties) and non-agricultural land use (Ocean County). These wells are distributed throughout the areal extent of the Kirkwood-Cohansey aquifer system (fig. 1).

Ultra-Clean Trace-Element Sampling Technique

The ultra-clean trace-element sampling protocol for public supply wells, which was developed for the study, is a modification of the surface-water low-level trace-element sampling protocol developed by Horowitz and others (1994). In many instances, the only difference is the equipment that is to be cleaned and used in the sampling procedure (for example, a churn splitter that is used to composite surface-water samples is not used in ground-water sampling). The protocol is designed to minimize low-level trace-element contamination of the samples through contact with sampling equipment, by sample

Table 1. Well-construction data for selected public supply wells screened in the Kirkwood-Cohansey aquifer system, New Jersey, 1993

[--, data not available; gal/min, gallons per minute; well locations shown in fig. 1]

Well number	County	Municipality	New Jersey permit number	Latitude (degrees)	Longitude (degrees)	Altitude of land surface (feet above sea level)	Depth of well (feet below land surface)	Top of open interval (feet below land surface)	Bottom of open interval (feet below land surface)	Discharge (gal/min)
01- 230	Atlantic	Hamilton	36-00441	392722	0743845	70	95.7	65.7	85.7	175
07- 490	Camden	Winslow	31-05543	394248	0745710	115	113	72	103	1,000
07- 497	Camden	Winslow	31-05534	394332	0745740	125	101	64	90	1,000
07- 603	Camden	Gloucester	31-16697	394414	0750016	140	120	100	120	503
07- 691	Camden	Gloucester	31-24727	394414	0750015	160	80	60.2	75	305
11- 3	Cumberland	Bridgeton	54-00003	392437	0751305	43	104	84	104	776
11- 13	Cumberland	Bridgeton	34-00598	392552	0751450	65	117	76.	117	525
11- 20	Cumberland	Bridgeton	54-00001	392641	0751329	80	111	91	111	510
11- 254	Cumberland	Vineland	35-05227	393208	0750245	90	160	130	160	1.030
11- 255	Cumberland	Vineland	35-00869	392850	0750103	90	174	140	170	100
11- 274	Cumberland	Bridgeton	34-01195	392722	0751235	100	110	70	110	439
[1]11- 278	Cumberland	Millville	35-00862	392238	0750420	70	191	161	191	--
11- 281	Cumberland	Hopewell	34-01194	392523	0751519	75	146	86	146	732
11- 361	Cumberland	Bridgeton	34-01945	392538	0751434	53	90	75	90	400
11- 712	Cumberland	Millville	35-12630	392235	0750432	75	222	162	217	1,280
15- 375	Gloucester	Monroe	31-14080	394010	0745845	148	147	118	147	805
15-1048	Gloucester	Monroe	31-27529	394217	0750039	162	144	100	141	492
15-1065	Gloucester	Washington	31-28782	394327	0750210	152	85	59.2	85	1,020
29- 88	Ocean	Dover	33-01147	395933	0741312	40	86	66	86	503
29- 428	Ocean	Lakehurst	29-01088	400039	0741930	64	36	26	36	100
29- 488	Ocean	Manchester	28-06885	395729	0742343	150	143	123	143	300
29- 586	Ocean	Manchester	32-01985	395714	0742112	100	90.1	61.1	81.1	501
29- 735	Ocean	Manchester	32-02893	395745	0742124	167	173	148	173	754

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[1]Well sealed in 1993

handling, and with airborne dust particles. Minor contamination of water samples from public supply wells by metallic casings, tubing, fittings, and solder cannot be avoided by using the ultra-clean sampling; therefore, 1 μg/L was maintained as the reporting limit in this study for all trace elements except Hg. Reporting limits less than 1 μg/L are feasible for polyvinyl chloride (PVC)-cased observation wells, in which low-level contamination can be avoided by careful sample collection in the absence of metallic casing, tubing, fittings, and solder. Turbidity was measured to determine the amount of suspended material in the water.

Five quality-assurance/quality-control samples consisting of three equipment blanks, one split sample, and one standard solution were analyzed at the NWQL to evaluate the presence of contamination and the precision and accuracy of the laboratory analyses. The equipment blanks and the split sample were collected randomly throughout the sampling period. To avoid any sampling or seasonal bias, the same personnel collected all the ground-water samples over a short interval (September 1993).

Sampling-Equipment Cleaning Procedures

Directions for the method used to clean sampling equipment during this study are given below, and consists of four steps; deionized water rinse, soap-solution rinse, nitric-acid rinse, and final deionized water rinse.

1. Put on powder-free latex gloves, apron, and safety glasses prior to cleaning equipment. Place 50-ft lengths of polyethylene tubing (3/8-in. outside diameter) and PVC hose barbs, hose connectors, and plastic clamps in a pre-soap and acid-washed designated tray filled with deionized (DI) water. (White or clear acid-resistant plastics (polyethylene or polypropylene) were used. Colored plastics were avoided because the metals used in the pigments could be leached by the cleaning acid.) Rinse each piece of equipment with DI water three times. Force DI water through the tubing for 10 minutes by using a peristaltic pump.

2. After the third rinse with DI water, fill tray with 8 L of DI water and 2 to 3 mL of phosphate-free soap. Allow tubing and hose barbs, connectors, and plastic clamps to soak in soap solution for 10 minutes in the tray. Scrub hose barbs, connectors, clamps, and outside of tubing with a non-metallic brush. Force soapy solution through tubing for 15 minutes by using a peristaltic pump. Rinse all hose barbs, connectors, and clamps three times with DI water, until no signs of soap remain. Force DI water through tubing for 10 minutes by using a peristaltic pump, until no signs of soap remain. Place polyethylene tubing, hose barbs, connectors, and clamps in a designated pre-cleaned second tray. Change gloves.

3. Make a 5-percent nitric acid solution with laboratory grade acid (8 L of DI water to 500 mL HNO_3) in the tray. (Nitric acid was used instead of hydrochloric acid because nitric acid has stronger oxidizing properties, which are essential for removing the sorbed trace elements. Nitric acid also tends to be free of trace elements, whereas hydrochloric acid is not. Nitric acid is a potential source of nitrate contamination in the sampling equipment; however, because samples were not analyzed for nutrients as part of this investigation, nitrate contamination was not a concern.) Force the acid solution through the tubing for 20 minutes, by using a peristaltic pump, to remove any trace elements that could be sorbed to the surface of the tubing. Meanwhile, soak the hose barbs, connectors, and clamps in the acid solution for 20 minutes. Rinse all hose barbs, connectors, and clamps three times with DI water. Force DI water through tubing for 10 minutes by using a peristaltic pump.

4. Allow all clean tubing and other clean equipment to air dry, then store in plastic bags marked with the date of cleaning. To prevent contamination from bacterial growth, use tubing within 5 days of cleaning.

Ultra-Clean Sample-Collection Procedures

A vehicle dedicated to low-level trace-element sampling was used. This van had not been used previously for any water-quality-sampling field work and, therefore, was not contaminated with mercuric chloride, which had been used as a preservative for nutrient samples. The van had been outfitted with a wooden floor and formica benchtop.

Nitric acid and potassium dichromate preservation ampules, clean tubing, latex gloves, shipping and ziplock storage bags, and polyethelyne pre-acid-washed sample bottles were placed in plastic bags and were stored in shipping boxes in the rear of the van. A clean shipping cooler used only for low-level trace-element sampling and ice were available for chilling and storing water samples.

A sampling routine was established to ensure the integrity of the samples. Tasks were divided between two people: One person, designated "dirty hands," was responsible for those tasks that could introduce contamination into the samples (working with the pump, monitoring meters) and, therefore, could not come in contact with the samples, the second person, designated "clean hands," was responsible for sample collection, handling, and preservation.

Upon arrival at the sampling site, the "clean hands" person, wearing latex gloves, prepared the van for sampling. A disposable polypropylene tarp was laid over the plywood floor. Portable glove-bag chamber frames--one large glove-bag chamber to be used for sample filtration and a smaller glove-bag chamber to be used for sample preservation--were assembled. The chamber frames were made of PVC 1/4-in. pipes that were pre-cleaned in a dishwasher, with a commercial dishwasher soap. The pipes fit together to make a square frame (A.J. Horowitz, U.S. Geological Survey, written commun., 1993). The chambers were completed by suspending large polyethylene bags from the frames to create a dust-free sample-collection and -preservation area. A separate preservation chamber was constructed for each sample preservative.

Sample bottles were pre-labeled and placed inside the large filtration chamber. A disposable 0.45-micron polysulfone-filter-medium tortuous-path capsule filter with a filtration area of 7.9 in^2 was used instead of a reusable plate filter; it was also placed into the filtration chamber. Disposable filters were used to avoid sample cross-contamination. Ampules of potassium dichromate (for mercury samples) were placed inside one preservation chamber; ampules of ultra-pure nitric acid (for other trace-element samples) were placed in the second.

The "dirty hands" person monitored pH, temperature, specific conductance, and dissolved-oxygen concentration, as described by Wood (1976). Samples were collected after meter readings stablized (three consecutive readings, at 5-minute intervals, that did not vary by more than 5 percent). When high-yielding public supply wells are sampled, the volume of water needed for adequate well purging is not a concern. Several thousand gallons of water were discharged from the wells prior to sample collection. Samples were collected by attaching a clean piece of tubing to a "raw-water" port on the wellhead. The polyethelyne sample tubing was fed into the sampling van through the window, was cut with non-metallic scissors, and was fed through a small hole punched in the back of the filtration-chamber bag. The flow of water into the sampling van was regulated at the port by the "dirty hands" person.

Sample bottles were filled in a specific sequence as described by Horowitz and others (1994): unfiltered, unpreserved (turbidity) in polyethelyne bottles; filtered, potassium dichromate- preserved (mercury) in acid-washed glass bottles; and filtered, ultra-pure nitric acid-preserved (other trace elements) in acid-washed polyethelyne bottles. After the unfiltered, unpreserved samples were collected, the flow of water into the sampling line was stopped to facilitate connection of the disposable capsule filter. About 1L of native water was used to condition the filter (Horowitz and others, 1994). The acid-rinsed glass and polyethelyne bottles were rinsed three times with filtered water prior to sample collection.

When all the samples had been collected, the "clean hands" person moved the sample bottles into the appropriate preservation chambers. Mercury samples were preserved with potassium dichromate in the first chamber, and the trace-element samples were preserved with ultra-pure nitric acid in the second chamber. Gloves were changed to avoid cross-contamination of samples each time a new preservation chamber was used. After all the samples were preserved, the bottles were placed in plastic bags and chilled.

Procedures for Collecting Equipment Blanks and Split Samples

A variety of samples were collected for quality assurance and quality control during the sampling period. These samples included splits, equipment blanks, and one standard solution. Sample splits provided quality control, and equipment blanks and the spiked sample were submitted as quality assurance. Sample splits were collected for about 55 percent of the samples (11 split samples). To compare laboratory results, 10 of those splits were submitted to the Rutgers laboratory for ICP-MS trace-element analysis. One split sample was submitted to the NWQL. Equipment blanks constituted 14 percent of the sample load (3 field blanks). One of the equipment blanks was split and sent to the Rutgers laboratory for analysis.

Split samples were prepared in the filtration chamber in the field. For samples to be analyzed for trace elements (except mercury), two 1-L acid-rinsed polyethelyne bottles were each rinsed three times with native filtered water. The first 1-L bottle was filled with a water sample. Water from the first bottle was poured into the second bottle. One-half of the contents of the second bottle was poured back into the first bottle. The 1-L sample of water was split into two 500-mL samples that had had contact with both sample bottles. Each split sample to be analyzed for trace elements was placed into the acid-preservation chamber, and 1 mL of ultra-pure nitric acid was added. Split samples to be analyzed for mercury were collected by using the same technique as that used to collect the split samples to be analyzed for trace elements, except that two 250-mL acid-washed glass bottles were used.

Equipment-blank samples were collected from a pre-cleaned polyethylene pipette jar (standpipe); a peristaltic pump was used to pump pre-analyzed, inorganic blank water through the sample tubing into a sample bottle. All the equipment blanks were collected inside a glove-bag filtration chamber inside the sampling vehicle. One set of equipment blanks was collected and split; one set of split samples was sent to the Rutgers laboratory and the other was sent to the NWQL for analysis.

Sample Analysis

Turbidity was determined by nephelometry (Fishman and Friedman, 1989) in the laboratory. Alkalinity was determined by incremental titration in the laboratory (Fishman and Friedman, 1989). Low concentrations (1 μg/L) of trace elements (Ba, Al, Ag, Be, Cd, Co, Cr, Cu, Mn, Mo, Ni, Pb, Sb, U, and Zn) in the samples were determined by ICP-MS.

Flameless atomic absorption (AA) hydride-generation techniques were used to determine the concentration of arsenic (Fishman and Friedman, 1989). The USEPA-approved cold-vapor flameless AA technique was used to determine the concentration of mercury (U.S. Environmental Protection Agency, 1979, p. 245). Graphite-furnace AA was used to determine the concentration of thallium (Fishman and Friedman, 1989). The analytical technique and the minimum reporting limit for each analyte are given in table 2.

The water-quality data presented in table 3 (at end of report) were determined from samples collected from the well network during 1986-90. Well 11-278 was sealed in 1993, prior to sampling, and well 11-712 was drilled by the purveyor in a similar location and to a similar depth as a replacement well for 11-278. Dissolved-oxygen concentration, pH, specific conductance, and temperature of samples collected during 1986-90 were measured in the field according to methods described by Wood (1976). All samples were analyzed at the NWQL. Alkalinity (as calcium carbonate) was determined in the laboratory by incremental titration. Concentrations of major cations and trace elements were determined by use of atomic emisson spectroscopy with an inductively coupled argon radio frequency plasma torch (ICP-AES). Concentrations of nutrients were determined by use of colorometric techniques outlined by Fishman and Friedman (1985); the method in which nitrogen (as nitrate plus nitrite) was used was equivalent to accepted USEPA methods (Fishman and Friedman, 1985; U.S. Environmental Protection Agency, 1979). Previously collected trace-element data from these wells were included in this report (table 3) to illustrate the benefit of determining trace-element concentrations at levels significantly lower than those achieved by the ICP-AES "metal scan" technique. Concentrations of trace elements such as Pb, Cu, Cr, and Cd, for which drinking-water regulations exist, were all previously reported as less than the detection limit of the ICP-AES technique. With the introduction of ICP-MS analyses, the actual concentrations of these constituents could be determined.

Determination of the concentrations of the 15 selected elements by ICP-MS required only a few milliliters of sample water. Six minutes were required to complete a sample-analysis cycle, which consists of sample uptake, three replicate mass-spectrometer integrations, and an equipment rinse with deionized water for each sample. A calibration curve was generated by using a calibration blank and multi-element standard solutions of known concentrations. Average short-term precision reported by the NWQL in its own internal quality-assurance program is 1.7 percent relative standard deviation for element concentrations ranging from 25 to 50 μg/L (Faires, 1993). Internal standard spikes are added to all blanks, calibration standards, samples, and quality-control samples to correct for instrumental drift and suppression or enhancement of analyte signals resulting from matrix effects. Several types of physical, chemical, or spectral interferences are

Table 2. Analytical technique, minimum reporting limit, minimum limit of detection, and precision for trace elements in water samples from the Kirkwood-Cohansey aquifer system, New Jersey, 1993

[µg/L, micrograms per liter; ICP-MS, inductively coupled plasma-mass spectrometry; AA, atomic adsorption; ICP-AES, inductively coupled plasma-atomic emission spectroscopy; DCP-AES, direct current plasma-atomic emission spectroscopy; --, data not available]

Trace element	Analytical technique[1]	Minimum reporting limit (µg/L)	Minimum detection limit (µg/L)	Relative standard deviation at a concentration of 1 µg/L (percent)[2]
Aluminum[3]	ICP-MS	1	1	140
Antimony	ICP-MS	1	.26	20
Barium	ICP-MS	1	.12	40
Beryllium	ICP-MS	1	.07	30
Cadmium	ICP-MS	1	.16	40
Chromium	ICP-MS	1	.16	30
Cobalt	ICP-MS	1	.07	30
Copper[3]	ICP-MS	1	.10	40
Lead[3]	ICP-MS	1	.18	30
Manganese	ICP-MS	1	.18	20
Molybdenum[3]	ICP-MS	1	.22	30
Nickel[3]	ICP-MS	1	.19	30
Silver	ICP-MS	1	.07	40
Uranium	ICP-MS	1	.16	20
Zinc	ICP-MS	1	.22	30
Arsenic	Flameless AA (hydride)	1	1	--
Mercury	Cold vapor flameless AA (hydride)	0.1	.1	--
Thallium	Graphite furnace AA	1	.1	--

[1] Analyses done by ICP-MS in this study were completed by using ICP-AES or DCP-AES in 1986-90.

[2] Relative standard deviation is less than or equal to 10 percent at concentrations of 5 µg/L for all elements analyzed by ICP-MS, except aluminum, for which the value is about 100 percent.

[3] Minimum reporting limit for this element is lower by a factor of 10 when ICP-MS is used than when ICP-AES or DCP-AES is used.

fully described and documented for ICP-MS techniques (Date and Gray, 1989). The trace-element analytes determined in this study have at least one isotope, which is free of such potential interference, that can be used for quantitative analysis.

The average method detection limit for the 15 trace-element analytes determined by using ICP-MS was 0.22 µg/L (Faires, 1993). The reporting limit for routine analysis of samples from the public supply wells was 1 µg/L for each element. The purpose of using the 1- µg/L reporting limit rather than the 0.22-µg/L detection limit is twofold: (1) to minimize the problems associated with possible field and laboratory contamination at the submicrogram-per-liter level and (2) to ensure a high degree of confidence in analytical results from the routine mode of operation for analysis of samples collected from an environment (public supply wells with iron casing, metal pump, copper tubing, brass fittings, and solder of various metal compositions) where low-level contamination with metals is highly probable.

Quality Assurance

Equipment blanks and duplicates were closely monitored to ensure the integrity of the samples was not compromised during the field sampling process. The accuracy of the ICP-MS analytical method was verified by the laboratory by means of analyses of internal standard-reference-water samples with certified or most probable values for the concentrations of the dissolved analytes. This accuracy was verified for the study by submitting a commercially-prepared reference standard sample containing known amounts of trace elements to the laboratory for analysis and comparing the analytically determined results to the known values.

CONCENTRATIONS OF TRACE ELEMENTS

Separate samples were collected for turbidity analyses because suspended particles and mobile colloid phases affect the transport of trace elements, especially Pb, Cr, Cu, and Ni (Backhus and others, 1993). Turbidity values for the samples generally were equal to or less than 1 NTU, except for samples from wells 01-230 and 29-428, which had turbidities of 20 and 8.7 NTU's, respectively. In 1993, well 01-230 was no longer being used by the purveyor and had not been pumped for many months prior to sampling, whereas well 29-428 was used intermittently by the purveyor. Backhus and others (1993) suggest that ground-water turbidity should be monitored to determine when a well has been adequately purged for sampling, especially in studies of trace elements. Trace elements tend to sorb to particle surfaces. Field monitoring of turbidity can ensure the collection of representative samples with reproducible trace-element concentrations by allowing sample collection to be delayed until the number of suspended particles is constant. Trace-element data collected from the public supply wells theoretically should be reproducible because the concentration of suspended colloids and particles is low.

Results of the trace-element analysis (table 4 at end of report) indicate that 5 of the 18 trace elements measured--Co, Cu, Pb, Hg, and Ni--typically were detected in low concentrations ranging from <0.1 to 29 µg/L (table 5) in most of the samples from the 22 wells; and 4 trace elements--Al, Ba, Mn and Zn--were detected in high concentrations (30 to 710 µg/L for Al, and 4.0 to 180 µg/L for Ba, Mn, and Zn) (table 5). Concentrations of As, Be, Cd, Cr, Sb, Mo, Tl, Ag, and U were less than the detection limit (1.0 µg/L) in samples from all the wells (table 4).

The concentration of Pb in one sample (well 11-13) exceeded the USEPA action level (15 µg/L) (U.S. Environmental Protection Agency, 1990) and in two other samples (wells 29-735 and 11-254) approached the action level (12 and 11 µg/L, respectively). The action level is a concentration set by the USEPA in lieu of a drinking-water maximum contaminant level (MCL). This level requires the purveyor, in addition to primary treatment (flocculant removal, bacterial control, and pH balance), to further treat the water by adding corrosion-controlling chemicals before distributing it to the customers. The proposed MCL goal for Pb in drinking water is zero. The concentration of Hg in the sample from well 29-428 (1.1 µg/L) approached the USEPA MCL of 2 µg/L, whereas samples from five other wells contained Hg in concentrations of 0.1 µg/L (the detection level) or 0.2 µg/L . The concentrations in samples from nine wells exceeded the USEPA secondary maximum contaminant level (SMCL) for Al (200 µg/L), and concentrations in two water samples (wells 07-691 and 11-254) exceeded the SMCL for Mn (50 µg/L) (U.S. Environmental Protection Agency, 1990).

Results of analyses of equipment-blank samples performed by using ICP-MS indicate that samples collected during 1993 by using the ultra-clean sampling technique were free of microgram-per-liter-level trace-element contamination (table 6). Concentrations of all elements except zinc in the equipment-blank samples were less than the reporting limit of 1 µg/L for ICP-MS. One blank sample contained a concentration of Zn of 1 µg/L, indicating that Zn contamination at the 1- to 2-µg/L level can occur randomly. Faires (1993) reported persistent problems with low-level Zn contamination in the laboratory. The equipment blank submitted to the Rutgers laboratory also was free of microgram-per-liter-level trace-element contamination (table 6) for the elements analyzed. Zinc was the only element with a concentration greater than 0.2 µg/L (0.2 µg/L detection limit at the Rutgers laboratory).

Table 5. Statistical summary and distribution of selected trace elements, pH, and turbidity in samples from selected public supply wells in the Kirkwood-Cohansey aquifer system, New Jersey, 1993

[<, less than]

Trace element or physical property	Number of values	Mean	Standard deviation	Median	Minimum	Maximum	25th percentile	75th percentile
Turbidity	20	1.74	4.69	0.2	0.10	20.0	0.2	0.6
pH	21	4.74	.33	4.7	4.20	5.40	4.5	5
Barium	22	62.63	40.29	53	20.0	180.0	30	78
Cobalt	22	1.75	1.70	1	<1	8.0	<1	2
Copper	22	12.93	8.14	12	<1	29.0	8	17
Lead	22	3.79	4.53	1.5	<1	16.0	<1	6
Manganese	22	23.72	18.08	18.5	4.0	82.0	13	27
Nickel	22	2.31	1.80	2	<1	8.0	1	3
Zinc	22	32.45	35.23	19.5	5.0	130.0	8	38
Aluminum	22	194.54	180.91	100	30.0	710.0	80	260
Mercury	22	.12	.22	<0.1	<0.1	1.1	<0.1	.1

Analysis of the commercially-prepared National Institute of Standards (NIST) standard solution CRM-390127 by ICP-MS at the NWQL produced values that were in agreement with the known concentrations of the elements in the solution. The standard sample was submitted as a blind quality-control sample. The relative percent difference between most of the analytically determined concentrations and the known values was 10 percent or less, except for concentrations of Ba, Cd, and Tl which differed from the known values by 12.8, 28, and 18.2 percent, respectively (table 7). The analytically determined concentrations of Cd and Tl were 0.5 to 1.0 μg/L higher than the known values, whereas the measured concentration of Ba was 0.5 μg/L lower than the known value. For 6 of the 10 elements (Ba, Co, Pb, Mn, Ni, and Zn) for which the analytically determined concentration did not match the known value, the analytically determined concentration was lower than the known value (table 6). The analytically determined concentrations of As, Cd, Tl, and Al were higher than the known values.

Results of analysis of the split sample collected from well 29-428 and analyzed at the NWQL agreed closely with results of analysis of the sample (table 4). All but one of the values differed by 5 percent or less; the difference in the concentration of Al between the sample and the split sample was 10 percent. This difference is attributed to inherent difficulties in analyzing for aluminum by using ICP-MS (Faires, 1993).

Constituent concentrations in the 10 split samples analyzed by using ICP-MS at the Rutgers laboratory showed good agreement (within 10 percent) (table 4) with the NWQL data for most elements, indicating that the ICP-MS analyses were accurate and precise and are reproducible between laboratories. Cd concentrations determined at the two laboratories could not be compared because the results from the NWQL were all below the reporting limit (table 4). Apparent low biases exist in the Rutgers laboratory data for Ba (-4.6 to -18 percent difference), Mn (-0.5 to -6 percent difference), and Zn (fig. 2a), compared to the NWQL data for these elements (table 7). Cr also showed an apparent low bias at the Rutgers laboratory. All the concentrations of Cr reported by the NWQL were below the reporting limit; the results from the Rutgers laboratory, however, indicated that all Cr concentrations were non-detectable (reported as zero) (table 4). Nickel is the only trace element that had an apparent high bias (fig. 2b) at the Rutgers laboratory, compared to the NWQL data. Isotopes of Pb also were analyzed at the Rutgers laboratory using ICP-MS. The ratios of ^{206}Pb to ^{207}Pb for ten of the public supply wells ranged from 1.1 to 1.27 (table 4).

Table 6. Results of analyses for concentrations of constituents in quality-assurance/quality-control equipment blanks and reference standard for water samples collected during 1993, New Jersey

[µg/L, microgram per liter; <, less than; --, data not available; NA, not analyzed]

Sample	Date	Time	Arsenic, dissolved (mg/L as As)	Barium, dissolved (mg/L as Ba)	Beryllium, dissolved (mg/L as Be)
[1]Blank 1	09-03-93	1345	<1	<1	<1
[2]Blank 2	09-03-93	1345	NA	.02	NA
[1]Blank 3	09-08-93	1240	<1	<1	<1
[1]Blank 4	09-28-93	1900	<1	<1	<1
[3]Standard	09-09-93	1445	21 (20)	11 (12.5)	5 (5)

Sample	Date	Cadmium, dissolved (µg/L as Cd)	Chromium, dissolved (µg/L as Cr)	Cobalt, dissolved (µg/L as Co)	Copper, dissolved (µg/L as Cu)	Lead, dissolved (µg/L as Pb)	Manganese, dissolved (µg/L as Mn)	Thallium, dissolved (µg/L as Tl)
Blank 1	09-03-93	<1.0	<1	<1	<1	<1	<1	<1
Blank 2	09-03-93	.01	0	NA	0	.07	NA	NA
Blank 3	09-08-93	<1.0	<1	<1	<1	<1	<1	<1
Blank 4	09-28-93	<1.0	<1	<1	<1	<1	<1	<1
Standard	09-09-93	4.0(3.0)	5 (5)	6 (6.25)	5 (5)	8 (8.75)	8 (8.75)	3 (2.5)

Sample	Date	Molybdenum, dissolved (µg/L as Mo)	Nickel, dissolved (µg/L as Ni)	Silver, dissolved (µg/L as Ag)	Zinc, dissolved (µg/L as Zn)	Antimony, dissolved (µg/L as Sb)	Aluminum, dissolved (µg/L as Al)	Mercury, dissolved (µg/L as Hg)	Uranium, natural, dissolved (µg/L as U)
Blank 1	09-03-93	<1.0	<1	<1.0	<1	<1	<1	<.1	<1.0
Blank 2	09-03-93	NA	0	NA	.26	NA	0	NA	NA
Blank 3	09-08-93	<1.0	<1	<1.0	2	<1	<1	<.1	<1.0
Blank 4	09-28-93	<1.0	<1	<1.0	1	<1	<1	<.1	<1.0
Standard	09-09-93	25 (25)	14 (15)	<1.0(<0.1)	16 (17.5)	<1 (--)	30 (28.75)	-- (--)	<1.0 (--)

[1] Equipment blanks analyzed at the U.S. Geological Survey National Water Quality laboratory

[2] Equipment blanks analyzed at the Rutgers University Chemistry Department laboratory

[3] Known values obtained from the National Institute of Standards and Technology given in parentheses

Table 7. Relative percent difference[1] in trace-element concentrations in split samples analyzed at the U.S. Geological Survey National Water Quality Laboratory and the Rutgers University Chemistry Department laboratory, and a quality-assurance/quality-control reference standard analyzed at the U.S. Geological Survey National Water Quality Laboratory, New Jersey, 1993

[NA, not analyzed; *, one or both trace-element concentrations below detection limit]

Type of sample, and well number for split samples[2]	Arsenic	Barium	Beryllium	Cadmium	Chromium	Cobalt	Copper
Split samples:							
07- 497	NA	4.6	NA	*	*	NA	37.2
07- 603	NA	8.7	NA	*	*	NA	2
07- 691	NA	11.8	NA	*	*	NA	16
11- 13	NA	9.0	NA	*	*	NA	5
11- 20	NA	11.6	NA	*	*	NA	9.1
11- 254	NA	6.3	NA	*	*	NA	12.9
11- 274	NA	11.8	NA	*	*	NA	6.6
11- 281	NA	18.3	NA	*	*	NA	5.1
15- 1065	NA	9.5	NA	*	*	NA	.4
29- 586	NA	13.3	NA	*	*	NA	4.8
Standard[3]	4.9	12.8	0	28.6	0	4.1	0

[1] Relative percent difference = (|S-D|)÷((S+D)÷2)x100 where S equals trace-element concentration in sample and D equals trace-element concentration in split sample.

[2] Trace-element concentrations in samples and split samples used to calculate relative percent difference are provided in table 4.

[3] Commercially prepared reference standard analysis results are provided in table 6.

Table 7. Relative percent difference[1] in trace-element concentrations in split samples analyzed at the U.S. Geological Survey National Water Quality Laboratory and the Rutgers University Chemistry Department laboratory, and a quality-assurance/quality-control reference standard analyzed at the U.S. Geological Survey National Water Quality Laboratory, New Jersey, 1993 --Continued

Type of sample, and well number for split samples[2]	Lead	Manganese	Thallium	Molybdenum	Nickel	Silver	Zinc	Aluminum
Split samples;								
07- 497	*	1.8	NA	NA	*	NA	21.6	1.5
07- 603	*	5.5	NA	NA	47.6	NA	.7	5.9
07- 691	*	3.4	NA	NA	60.8	NA	9.9	2.8
11- 13	3.1	3.2	NA	NA	2	NA	12.2	1.3
11- 20	1.3	9.3	NA	NA	28.9	NA	3.8	.7
11- 254	8.5	.5	NA	NA	62.1	NA	1.3	1.7
11- 274	10.3	.6	NA	NA	12.2	NA	4.4	7.3
11- 281	45.4	2.9	NA	NA	25.1	NA	10.5	12.2
15- 1065	8.3	6.5	NA	NA	13.1	NA	32.5	.6
29- 586	8.2	3.3	NA	NA	53.3	NA	13.2	.2
Standard[3]	9	9	18.2	0	6.9	*	9	4.3

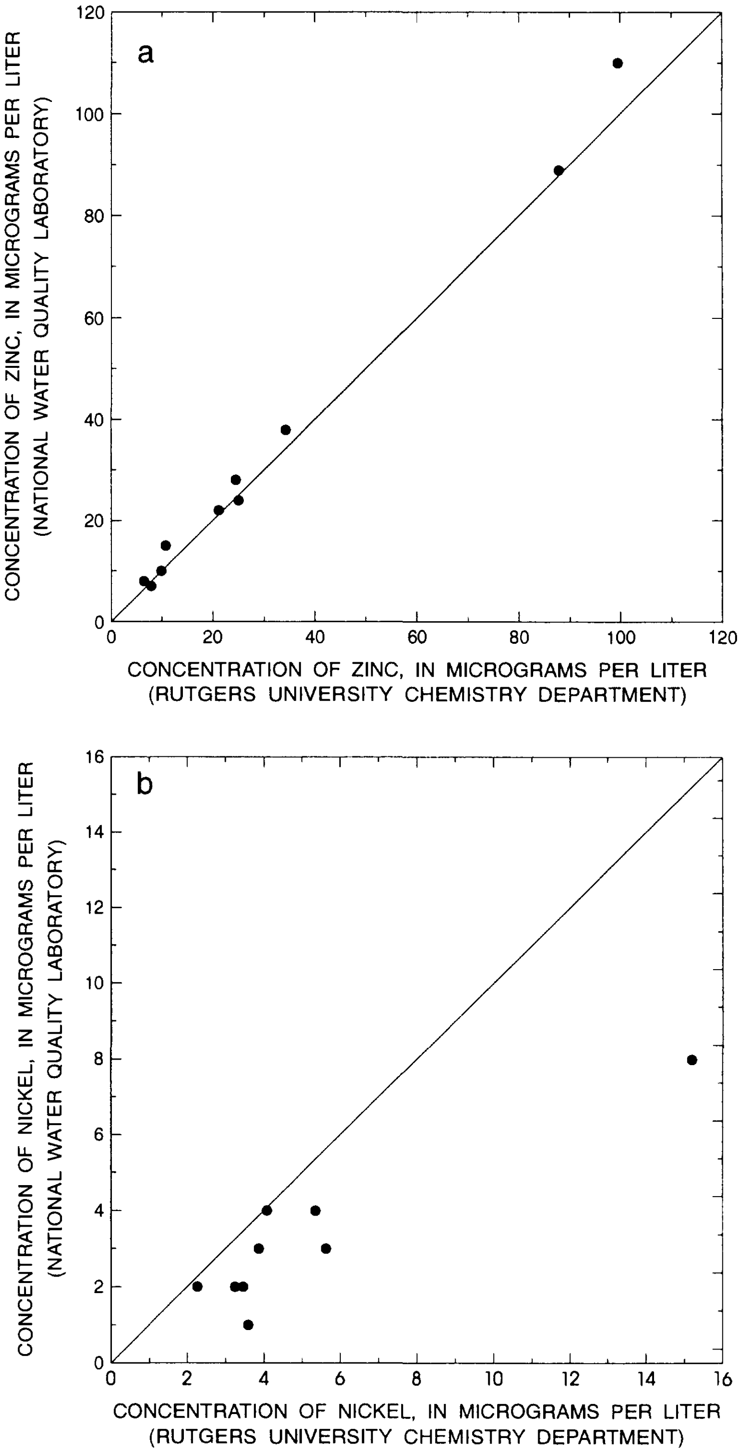

Figure 2. Concentrations of (a) zinc and (b) nickel in quality-assurance/quality-control split samples analyzed at the U.S. Geological Survey National Water Quality Laboratory and the Rutgers University Chemistry Department laboratory, New Jersey, 1993.

A wilcoxon signed rank test (Helsel and Hirsch, 1992) was used to test whether there were significant differences between the ICP-MS concentration values of trace elements in the water-quality samples analyzed at the NWQL and those in the samples analyzed at the Rutgers laboratory. Differences were considered significant when the p-value was less than or equal to 0.05. Results of the test indicated a significant difference between Cr, Ni and Zn concentrations (p-values of 0.002 for Cr and Ni, 0.04 for Zn) from the two laboratories. The differences for Zn and Ni are illustrated in figure 2. No significant difference was determined for Ba, Cu, Mn, and Al.

The quality-assurance data from the NWQL and the Rutgers laboratory showed good agreement, which indicates that the measured trace-element concentrations were representative, precise, and accurate. The results of analysis of the equipment blanks show that the ultra-clean sampling protocol eliminates microgram-per-liter-level trace-element contamination of the samples. However, even though the quality-assurance data from the NWQL agreed well between the split sample and the reference standard sample of known concentrations, statistical conclusions on precision and accuracy cannot be made because of the small number of samples (one split sample, one standard sample).

SUMMARY

Water samples collected during 1993 from 22 public supply wells screened in the Kirkwood- Cohansey aquifer system and located in agricultural and non-agricultural areas were analyzed for arsenic (As), barium (Ba), beryllium (Be), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), manganese (Mn), thallium (Tl), molybdenum (Mo), nickel (Ni), silver (Ag), zinc (Zn), antimony (Sb), aluminum (Al), mercury (Hg), and uranium (U). Low-level trace-element sampling protocols were used to collect water samples, and inductively coupled plasma-mass spectrometry (ICP-MS) analyses capable of producing accurate and precise results at the microgram-per-liter level (reporting limit 1 μg/L for all elements except Hg which had a 0.1 μg/L reporting limit) were used to analyze those samples. Although the ICP-MS analytical technology can produce results at the required level of precision and accuracy, sampling protocols must ensure against microgram-per-liter-level trace-element contamination; hence the need to design and test an "ultra-clean" sampling protocol during the study. Trace-element concentrations determined during 1986-90 by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) for water samples from 21 of the same wells are included in this report for comparison with 1993 water-quality data.

In general, turbidity of the samples was equal to or less than 1 NTU, except for that of the samples from two infrequently used wells indicating that trace elements carried on particulates did not compromise sample integrity. Results of the trace-element analysis indicate that 5 of the measured 18 trace elements analyzed for--Co, Cu, Pb, Hg, and Ni--

were detectable in concentrations ranging from <0.1 to 29 µg/L in most of the samples from the 22 wells, whereas 4 elements--Al, Ba, Mn, and Zn--were detected in a higher range of concentrations in most samples (from 30 to 710 µg/L for Al, and from 4.0 to 180 µg/L for Ba, Mn, and Zn). Concentrations of As, Be, Cd, Cr, Sb, Mo, Tl, Ag, and U in samples from all wells were less than the detection limit (1 µg/L). The concentration of Pb (16 µg/L) in one water sample exceeded the U.S. Environmental Protection Agency's (USEPA) action level (15 µg/L), and the concentration of Hg in the sample from well 29-428 (1.1 µg/L) approached the USEPA maximum contamination limit MCL of 2 µg/L.

Sampling-equipment blanks were demonstrated to be free of low-level trace-element contamination. Concentrations of all trace elements analyzed for by using ICP-MS were less than the reporting limit of 1 µg/L for the U.S. Geological Survey National Water Quality Laboratory (NWQL) and 0.2 µg/L for the Rutgers University Chemistry Department laboratory (Rutgers laboratory). One blank sample analyzed at the NWQL contained Zn in a concentration of 1 µg/L, and the blank sample analyzed at the Rutgers laboratory contained Zn in a concentration of 0.26 µg/L (0.2 µg/L detection limit at the Rutgers laboratory) , indicating random Zn contamination at low levels cannot be completely eliminated.

Analysis of the blindly submitted, commercially prepared National Institute of Standards reference standard solution by ICP-MS at the NWQL produced results that were in agreement with the known concentrations of the trace elements. The relative percent difference between the analytically determined concentrations and the known values was 10 percent or less, except for three elements--Ba, Cd and Tl. The analytically determined concentrations of Cd and Tl were 0.5 to 1.0 µg/L higher than the known values, whereas that of Ba was 0.5 µg/L lower.

The relative difference between the trace-element concentrations in a sample analyzed by the NWQL and those in the split sample was 5 percent or less, with the exception of aluminum, for which the difference was 10 percent; this large difference is attributed to inherent difficulties in analyzing for this trace element by ICP-MS.

Concentrations of trace elements determined in 10 split samples analyzed at the NWQL and at the Rutgers laboratory showed good agreement (within 10 percent), except for Ni. Results of analyses conducted at the Rutgers laboratory indicated an apparent low bias for concentrations of Ba, Mn, and Zn in most samples compared to those determined at the NWQL. Concentrations of Cr reported by the NWQL were all less than the reporting limit; however, Cr was not detected at the Rutgers laboratory. Nickel was the only trace element with a high bias in concentrations measured at the Rutgers laboratory relative to those measured at the NWQL; every concentration was higher than the corresponding concentration from the NWQL. These results indicate that the sampling procedure is effective, that both laboratories are free of low-level trace-element contamination (except for Zn), and that analyses with ICP-MS can be accurate, precise, and reproducible between laboratories, provided the integrity of the sample is not compromised during sampling. The trace-element concentrations determined in the samples from the public supply wells during this study can be used, therefore, as a baseline to determine, for example, whether the application of agricultural chemicals over time results in increasing concentrations and a redistribution of trace elements in the aquifer system.

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GLOSSARY

Aquifer: A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Dissolved: Chemical constituents in a water sample that pass through a 0.45-micrometer membrane filter. This is a convenient operational definition used by Federal agencies that collect water data. Determinations of "dissolved" constituents are made on subsamples of the filtrate.

Element: Any substance identified by a specific number of protons in its nucleus (known as the atomic number) that cannot be separated into smaller component substances except by nuclear disintegration (radioactivity).

Equipment blank: A blank solution that is subjected to all aspects of sample collection, field processing, preservation, transportation to the laboratory, and laboratory handling as an environmental sample, but is generated in the relatively controlled environment of a laboratory.

Field-measured characteristics: A phrase used to identify characteristics determined in the field when the water sample is collected. Water temperature, specific conductance, pH, and dissolved-oxygen concentration are considered field-measured characteristics in this study.

Isotope: Any of two or more forms of an element that have different atomic weights due to different numbers of neutrons found in the nucleus. The chemical properties of isotopes are identical.

Maximum contamination level (MCL): Maximum permissible level of a contaminant in water which is delivered to the free-flowing outlet of the ultimate user of a public water system.

Maximum contamination level goal: A non-enforceable concentration of a drinking water contaminant that is protective of adverse human health effects and allows an adequate margin of safety.

GLOSSARY--Continued

Micrograms per liter (µg/L): A unit expressing the concentration of chemical constituents in solution as the mass (microgram = 1×10^{-6} gram) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. One microgram per liter is approximately equal to 1 part per billion (ppb) in aqueous solutions of low dissolved-solids concentration.

Milligrams per liter (mg/L): A unit expressing the concentration of chemical constituents in solution as the mass (milligram= 1×10^{-3} gram) of solute per unit volume (liter) of water. For water containing less than 7,000 mg/L dissolved solids, the numerical value for milligrams per liter of a constituent is the same as for the concentration in parts per million (ppm).

Minimum reporting limit: For a given type of sample and analytical procedure, the concentration value below which the presence of the constituent being analyzed can be neither verified nor denied. Minimum detection limits can be identified in the tables of this report by a "less than" (<) symbol preceding a numerical value. The reported minimum detection limit can vary from analysis to analysis for any single constituent.

Nephelometric turbidity unit (NTU): A unit expressing the measurement of the intensity of light scattered by suspended particles in the water column.

Picocuries per liter (pCi/L): A unit expressing the concentration of radioactive constituents in solution as the radioactivity (picocuries) of the solute per unit volume (liter) of water. One picocurie is equal to 1×10^{-12} Curies, where one Curie is the amount of radiation emitted by one gram of radium. One picocurie represents 2.2 radioactive decays per second.

Radioactivity: The disintegration of the nucleus of an atom of element giving off energy in the forms of alpha (a nucleus of a helium atom) and beta (an electron) particles and in gamma rays. A different element is produced by the radioactive decay.

Radionuclide: A specific isotope of an element that is radioactive (will undergo a form of radioactive decay).

Replicate samples: A group of samples, collected in a manner such that the samples are thought to be essentially identical in composition. There are many types of replicate samples, each of which may yield slightly different results in a dynamic hydrologic setting.

GLOSSARY--Continued

Secondary maximum contaminant level (SMCL): Contaminants that affect the aesthetic quality of drinking water. At high concentrations, health implications as well as aesthetic degradation may also exist. SMCLs are not Federally enforceable but are intended as guidelines for State agencies.

Split sample: A type of replicate sample in which a sample is split into subsamples that are contemporaneous in time and space.

Table 3. Physical properties of, and concentrations of, trace elements, nutrients, calcium, magnesium, and selected radioactive elements and radionuclides in, water samples from public supply wells in the Kirkwood-Cohansey aquifer system, New Jersey, 1986-90

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picocuries per liter; <, less than; --, data not available; Ra, radium; trace-element analyses were performed by using inductively coupled plasma-atomic emission spectroscopy or direct current plasma-atomic emission spectroscopy]

Well number	Date	Temperature water (°C)	Specific conductance (µS/cm)	Oxygen, dissolved (mg/L)	pH water, field (standard units)	Arsenic, dissolved (µg/L as As)	Barium, dissolved (µg/L as Ba)	Beryllium, dissolved (µg/L as Be)
01- 230	12-06-88	14.0	49	4.4	5.2	<1	36	<0.5
07- 490	12-16-88	11.5	92	5.1	5.3	<1	56	<.5
07- 497	12-16-88	12.5	54	5.0	5.7	<1	29	<.5
07- 603	12-02-88	13.0	127	7.5	5.0	<1	130	<.5
07- 691	07-18-90	13.5	66	4.1	5.1	--	55	<.5
11- 3	12-07-88	12.5	81	9.7	4.5	<1	77	<.5
		12.5	81	9.7	4.5	<1	77	<.5
11- 13	12-06-88	12.5	121	6.2	4.6	<1	63	<.5
11- 20	12-06-88	14.0	93	5.2	4.8	<1	58	<.5
11- 254	11-30-88	12.0	97	1.4	4.3	<1	86	<.5
11- 255	11-30-88	12.5	73	4.1	4.4	<1	51	<.5
11- 274	12-08-88	12.5	125	6.1	4.7	<1	180	<.5
[1]11- 278	12-09-88	11.5	38	6.9	5.1	<1	27	<.5
11- 281	12-07-88	12.5	142	5.9	4.8	<1	100	<.5
11- 361	12-07-88	13.5	120	5.1	4.6	<1	55	<.5
15- 375	11-20-86	13.0	100	2.8	4.5	--	82	<.5
15-1048	08-15-90	12.5	30	6.7	5.0	--	11	<.5
15-1065	07-17-90	13.5	92	8.7	4.9	--	180	<.5
29- 88	07-12-90	13.0	126	6.2	4.7	<1	57	<.5
29- 428	07-12-90	13.5	129	3.1	5.1	<1	25	<.5
29- 488	07-13-90	13.0	34	.1	4.7	<1	20	.6
29- 586	07-11-90	14.0	77	5.5	4.7	<1	30	<.5
29- 735	07-11-90	13.0	57	3.3	4.5	<1	28	.6

[1] Well sealed in 1993

Table 3. Physical properties of, and concentrations of, trace elements, nutrients, calcium, magnesium, and selected radioactive elements and radionuclides in, water samples from public supply wells in the Kirkwood-Cohansey aquifer system, New Jersey 1986-90--Continued

Well number	Date	Cadmium, dissolved (μg/L as Cd)	Chromium, dissolved (μg/L as Cr)	Cobalt, dissolved (μg/L as Co)	Copper, dissolved (μg/L as Cu)	Lead, dissolved (μg/L as Pb)	Manganese, dissolved (μg/L as Mn)	Molybdenum, dissolved (μg/L as Mo)	Nickel, dissolved (μg/L as Ni)	Silver, dissolved (μg/L as Ag)
01- 230	12-06-88	<1	<5	<3	30	<10	44	<10	<10	<1.0
07- 490	12-16-88	<1	<5	<3	<10	<10	11	<10	<10	<1.0
07- 497	12-16-88	<1	<5	<3	<10	<10	16	<10	<10	<1.0
07- 603	12-02-88	<1	<5	<3	<10	<10	31	<10	<10	<1.0
07- 691	07-18-90	<1	<5	<3	<10	<10	76	<10	<10	<1.0
11- 3	12-07-88	<1	<5	<3	40	<10	17	<10	<10	<1.0
		<1	<5	<3	40	10	17	<10	<10	<1.0
11- 13	12-06-88	<1	<5	<3	10	<10	26	<10	<10	<1.0
11- 20	12-06-88	<1	<5	<3	40	<10	11	<10	<10	1.0
11- 254	11-30-88	<1	<5	6	40	<10	60	<10	<10	<1.0
11- 255	11-30-88	<1	<5	<3	20	<10	14	<10	<10	<1.0
11- 274	12-08-88	<1	<5	<3	40	<10	27	<10	<10	<1.0
11- 278	12-09-88	<1	<5	<3	<10	<10	5	<10	<10	<1.0
11- 281	12-07-88	<1	<5	<3	40	10	19	<10	<10	<1.0
11- 361	12-07-88	<1	<5	<3	20	<10	20	<10	<10	<1.0
15- 375	11-20-86	1	--	<3	20	<10	21	<10	--	--
15-1048	08-15-90	<1	<5	<3	<10	<10	8	<10	<10	<1.0
15-1065	07-17-90	<1	<5	<3	<10	<10	28	<10	<10	<1.0
29- 88	07-12-90	<1	<5	<3	<10	<10	31	<10	<10	<1.0
29- 428	07-12-90	<1	<5	<3	10	<10	48	<10	<10	<1.0
29- 488	07-13-90	<1	<5	<3	<10	<10	8	<10	<10	<1.0
29- 586	07-11-90	<1	<5	<3	80	<10	18	<10	<10	<1.0
29- 735	07-11-90	<1	<5	<3	20	<10	11	<10	<10	<1.0

Table 3. Physical properties of, and concentrations of, trace elements, nutrients, calcium, magnesium, and selected radioactive elements and radionuclides in, water samples from public supply wells in the Kirkwood-Cohansey aquifer system, New Jersey 1986-90--Continued

Well number	Date	Mercury, dissolved (µg/L as Hg)	Zinc, dissolved (µg/L as Zn)	Aluminum, dissolved (µg/L as Al)	Uranium, natural, dissolved (µg/L as U)	Uranium natural, 2 sigma water, dissolved (µg/L)	Radium-226, dissolved radon method (pCi/L)	Ra-226 2 sigma water, dissolved (pCi/L)	Radium-228, dissolved (pCi/L as Ra-228)	Ra-228 2 sigma water, dissolved (pCi/L)
01- 230	12-06-88	<0.1	81	40	<0.01	--	0.43	--	1.2	--
07- 490	12-16-88	<.1	10	40	.01	--	1.7	--	3.0	--
07- 497	12-16-88	<.1	4	40	.03	--	.87	--	<1.0	--
07- 603	12-02-88	.2	10	100	.19	--	4.1	--	3.2	--
07- 691	07-18-90	--	34	30	.01	<1.0	2.5	.340	1.7	.7
11- 3	12-07-88	--	120	150	.02	--	1.9	--	3.6	--
		--	120	150	.03	--	2.1	--	3.4	--
11- 13	12-06-88	--	6	310	.14	--	4.2	--	3.3	--
11- 20	12-06-88	--	31	280	.04	--	1.9	--	2.7	--
11- 254	11-30-88	--	72	530	.06	--	2.1	--	3.3	--
11- 255	11-30-88	--	21	350	.02	--	1.5	--	1.8	--
11- 274	12-08-88	--	<3	130	.09	--	4.0	--	3.0	--
11- 278	12-09-88	--	24	90	.02	--	.90	--	1.3	--
11- 281	12-07-88	--	26	60	.01	--	2.5	--	2.1	--
11- 361	12-07-88	--	15	700	.07	--	1.8	--	2.3	--
15- 375	11-20-86	--	25	220	--	--	--	--	--	--
15-1048	08-15-90	--	11	200	.02	--	.31	--	<1.0	--
15-1065	07-17-90	--	26	110	.02	<1.0	2.2	.310	2.2	.9
29- 88	07-12-90	--	30	170	.04	<1.0	2.4	.330	1.7	--
29- 428	07-12-90	--	24	190	.04	<1.0	1.2	.160	2.1	--
29- 488	07-13-90	--	6	100	<.01	<1.0	.18	.030	<1.0	--
29- 586	07-11-90	--	4	110	.07	<1.0	1.6	.220	1.7	--
29- 735	07-11-90	--	11	400	.05	<1.0	.92	.130	1.9	--

Table 3. Physical properties of, and concentrations of, trace elements, nutrients, calcium, magnesium, and selected radioactive elements and radionuclides in, water samples from public supply wells in the Kirkwood-Cohansey aquifer system, New Jersey 1986-90--Continued

Well number	Date	Alkalinity, lab (mg/L as $CaCO_3$)	Nitrogen, ammonia dissolved (mg/L as N)	Nitrogen, nitrite dissolved (mg/L as N	Nitrogen, ammonia and organic dissolved (mg/L as N)	Nitrogen, $NO_2 + NO_3$ dissolved (mg/L as N)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)
01- 230	12-06-88	4.0	<0.010	0.010	0.20	1.10	1.3	0.78
07- 490	12-16-88	5.0	<.010	<.010	.60	4.90	4.6	2.8
07- 497	12-16-88	8.0	.040	<.010	.20	.800	3.3	1.7
07- 603	12-02-88	2.0	<.010	<.010	.50	5.60	7.2	4.8
07- 691	07-18-90	3.1	.060	<.010	<.20	.800	2.8	.95
11- 3	12-07-88	<1.0	<.010	<.010	.20	3.50	2.3	2.2
		<1.0	<.010	<.010	.60	3.50	2.3	2.1
11- 13	12-06-88	1.0	<.010	<.010	.60	6.20	4.6	4.3
11- 20	12-06-88	1.0	.110	<.010	.30	3.20	3.4	2.5
11- 254	11-30-88	<1.0	<.010	<.010	.20	2.00	3.2	2.2
11- 255	11-30-88	<1.0	<.010	<.010	.20	3.10	2.5	1.5
11- 274	12-08-88	1.0	<.010	<.010	1.1	7.40	4.8	5.5
11- 278	12-09-88	2.0	.010	.010	.20	1.40	1.6	.83
11- 281	12-07-88	2.0	<.010	<.010	1.5	7.50	8.2	5.4
11- 361	12-07-88	<1.0	<.010	<.010	.30	4.30	5.4	3.3
15- 375	11-20-86	2.0	.018	--	--	3.30	3.2	2.2
15-1048	08-15-90	2.2	<.010	<.010	<.20	.400	1.3	.41
15-1065	07-17-90	2.1	.020	<.010	.50	4.70	4.6	3.8
29- 88	07-12-90	1.9	<.010	<.010	.60	3.00	2.7	2.5
29- 428	07-12-90	2.9	.030	<.010	.50	1.30	3.7	.99
29- 488	07-13-90	1.5	.020	<.010	<.20	<.100	.24	.24
29- 586	07-11-90	1.4	<.010	<.010	.40	1.30	1.1	1.2
29- 735	07-11-90	<1.0	.020	<.010	<.20	.400	.53	.55

Table 4. Physical properties of, concentrations of trace elements in, and lead isotope ratios in water samples from selected public supply wells in the Kirkwood-Cohansey aquifer system, New Jersey, 1993

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 °C; NTU, national turbidity units; mg/L, milligrams per liter; µg/L, microgram per liter; <, less than; --, data not available]

Well number	Date	Temperature, water (°C)	Turbidity (NTU)	Specific conductance (µS/cm)	Oxygen, dissolved (mg/L)	pH, water, field (standard units)
01- 230	09-17-93	15	20.0	45	4.9	5.1
07- 490	09-08-93	14	.30	91	5.0	4.2
07- 497	09-08-93	13	.60	54	5.4	5.2
07- 603	09-10-93	14	.10	109	7.7	5.0
07- 691	09-10-93	13	.30	78	3.4	5.3
11- 3	09-29-93	14	.20	118	11.2	4.6
11- 13	09-28-93	14	.20	129	5.8	4.6
11- 20	09-27-93	15	.20	90	5.6	4.7
11- 254	09-24-93	14	1.5	102	1.8	4.4
11- 255	09-24-93	14	.20	74	4.1	4.5
11- 274	09-27-93	14	.20	126	7.1	4.7
11- 281	09-28-93	13	.60	133	6.8	4.3
11- 361	09-28-93	14	.20	122	5.3	4.7
11- 712	09-15-93	12.5	.20	36	7.5	5.0
15- 375	09-01-93	13	--	95	2.9	4.8
15-1048	09-01-93	13	--	60	6.6	5.0
15-1065	09-08-93	13	.20	103	8.0	4.5
29- 88	09-07-93	13	.20	110	6.2	4.5
29- 428	09-09-93	15	8.7	90	2.7	5.4
	09-09-93	--	--	--	--	--
29- 488	09-03-93	13	.70	26	.5	4.4
29- 586	09-02-93	14	.10	76	5.8	4.7
29- 735	09-02-93	13	.10	59	3.7	--

Table 4. Physical properties of, concentrations of trace elements in, and lead isotope ratios in water samples from selected public supply wells in the Kirkwood-Cohansey aquifer system, New Jersey, 1993--Continued

Well number	Date	Arsenic, dissolved (µg/L as As)	Barium[1], dissolved (µg/L as Ba)	Beryllium, dissolved (µg/L as Be)	Cadmium[1], dissolved (µg/L as Cd)	Chromium[1], dissolved (µg/L as Cr)	Cobalt, dissolved (µg/L as Co)	Copper[1], dissolved (µg/L as Cu)
01- 230	09-17-93	<1	35	<1	<1	<1	2	25
07- 490	09-08-93	<1	59	<1	<1	<1	1	8
07- 497	09-08-93	<1	30 (28.6)	<1	<1 (.05)	<1 (0)	<1	3 (2.1)
07- 603	09-10-93	<1	98 (89.8)	<1	<1 (.08)	<1 (0)	2	11 (11.2)
07- 691	09-10-93	<1	61 (54.2)	<1	<1 (.08)	<1 (0)	1	10 (11.7)
11- 3	09-29-93	<1	100	<1	<1	<1 (0)	2	12
11- 13	09-28-93	<1	72 (65.8)	<1	<1 (.23)	<1 (0)	3	12 (11.4)
11- 20	09-27-93	<1	51 (45.9)	<1	<1 (.10)	<1 (0)	<1	18 (19.7)
11- 254	09-24-93	<1	78 (73.3)	<1	<1 (.26)	<1 (0)	8	29 (33.0)
11- 255	09-24-93	<1	53	<1	<1	<1	<1	12
11- 274	09-27-93	<1	180 (149.8)	<1	<1 (.14)	<1 (0)	2	3 (2.9)
11- 281	09-28-93	<1	91 (80.9)	<1	<1 (.19)	<1 (0)	1	16 (17.1)
11- 361	09-28-93	<1	53	<1	<1	<1	2	2
11- 712	09-15-93	<1	22	<1	<1	<1	<1	16
15- 375	09-01-93	<1	69	<1	<1	<1	3	3
15- 1048	09-01-93	<1	28	<1	<1	<1	<1	20
15- 1065	09-08-93	<1	140 (127.3)	<1	<1 (.07)	<1 (0)	2	10 (10.0)
29- 88	09-07-93	<1	53	<1	<1	<1	4	17
29- 428	09-09-93	<1	22	<1	<1	<1	<1	14
	09-09-93	<1	22	<1	<1	<1	<1	15
29- 488	09-03-93	<1	20	<1	<1	<1	<1	<1
29- 586	09-02-93	<1	33 (28.9)	<1	<1 (.1)	<1 (0)	1	29 (30.4)
29- 735	09-02-93	<1	30	<1	<1	<1	1	14

Table 4. Physical properties of, concentrations of trace elements in, and lead isotope ratios in water samples from selected public supply wells in the Kirkwood-Cohansey aquifer system, New Jersey, 1993 --Continued

Well number	Date	Lead[1], dissolved (μg/L as Pb)	^{206}Pb/^{207}Pb, isotope ratio	Manganese[1], dissolved (μg/L as Mn)	Thallium, dissolved (μg/L as Tl)	Molybdenum, dissolved (μg/L as Mo)	Nickel[1], dissolved (μg/L as Ni)
01- 230	09-17-93	3	--	21	<1	<1	2
07- 490	09-08-93	2	--	25	<1	<1	1
07- 497	09-08-93	<1 (.2)	(1.23)	16 (15.7)	<1	<1	<1 (3.6)
07- 603	09-10-93	<1 (.3)	(1.10)	24 (22.7)	<1	<1	2 (3.3)
07- 691	09-10-93	<1 (.5)	(1.12)	82 (79.3)	<1	<1	3 (5.6)
11- 3	09-29-93	1	--	16	<1	<1	3
11- 13	09-28-93	16 (16.5)	(1.19)	32 (31.0)	<1	<1	4 (4.1)
11- 20	09-27-93	6 (6.1)	(1.21)	9 (9.9)	<1	<1	4 (5.4)
11- 254	09-24-93	11 (12.0)	(1.20)	61 (61.3)	<1	<1	8 (15.2)
11- 255	09-24-93	<1	--	13	<1	<1	2
11- 274	09-27-93	1 (.6)	(1.24)	25 (24.3)	<1	<1	3 (3.9)
11- 281	09-28-93	10 (9.0)	(1.27)	17 (17.1)	<1	<1	2 (2.3)
11- 361	09-28-93	<1	--	17	<1	<1	3
11- 712	09-15-93	1	--	4	<1	<1	1
15- 375	09-01-93	5	--	20	<1	<1	4
15- 1048	09-01-93	1	--	8	<1	<1	<1
15- 1065	09-08-93	3 (2.8)	(1.18)	35 (32.8)	<1	<1	2 (2.3)
29- 88	09-07-93	6	--	27	<1	<1	3
29- 428	09-09-93	<1	--	36	<1	<1	<1
		<1	--	36	<1	<1	1
29- 488	09-03-93	<1	--	6	<1	<1	<1
29- 586	09-02-93	2 (2.2)	(1.20)	17 (16.4)	<1	<1	2 (3.5)
29- 735	09-02-93	12	--	11	<1	<1	2

Table 4. Physical properties of, concentrations of trace elements in, and lead isotope ratios in water samples from selected public supply wells in the Kirkwood-Cohansey aquifer system, New Jersey, 1993 –Continued

Well number	Date	Silver, dissolved (μg/L as Ag)	Zinc[1], dissolved (μg/L as Zn)	Antimony, dissolved (μg/L as Sb)	Aluminum[1], dissolved (μg/L as Al)	Mercury, dissolved (μg/L as Hg)	Uranium, natural, dissolved (μg/L as U)	Alkalinity, lab (mg/L as $CaCO_3$)
01- 230	09-17-93	<1.0	47	<1	40	<0.1	<1	5.4
07- 490	09-08-93	<1.0	12	<1	80	<.1	<1	3.0
07- 497	09-08-93	<1.0	8 (6.4)	<1	60 (60.9)	<.1	<1	4.0
07- 603	09-10-93	<1.0	10 (9.9)	<1	80 (75.5)	.1	<1	3.0
07- 691	09-10-93	<1.0	110 (99.6)	<1	30 (29.2)	<.1	<1	7.5
11- 3	09-29-93	<1.0	64	<1	200	<.1	<1	<1.0
11- 13	09-28-93	<1.0	7 (7.9)	<1	330 (325.8)	<.1	<1	1.1
11- 20	09-27-93	<1.0	22 (21.2)	<1	260 (256.2)	<.1	<1	<1.0
11- 254	09-24-93	<1.0	89 (87.9)	<1	580 (589.7)	.1	<1	<1.0
11- 255	09-24-93	<1.0	17	<1	360	<.1	<1	<1.0
11- 274	09-27-93	<1.0	24 (25.1)	<1	110 (118.3)	<.1	<1	<1.0
11- 281	09-28-93	<1.0	38 (34.2)	<1	60 (53.1)	<.1	<1	<1.0
11- 361	09-28-93	<1.0	5	<1	710	<.1	<1	<1.0
11- 712	09-15-93	<1.0	10	<1	50	<.1	<1	1.8
15- 375	09-01-93	<1.0	7	<1	230	<.1	<1	--
15- 1048	09-01-93	<1.0	30	<1	210	<.1	<1	--
15- 1065	09-08-93	<1.0	15 (10.8)	<1	90 (89.5)	.2	<1	4.5
29- 88	09-07-93	<1.0	130	<1	150	.2	<1	1.6
29- 428	09-09-93	<1.0	26	<1	90	1.1	<1	1.8
		<1.0	27	<1	100	1.0	<1	--
29- 488	09-03-93	<1.0	8	<1	90	<.1	<1	<1.0
29- 586	09-02-93	<1.0	28 (24.5)	<1	90 (89.8)	.2	<1	--
29- 735	09-02-93	<1.0	7	<1	380	<.1	<1	--

[1] Concentration in parentheses and lead isotope ratios are those measured in split water samples analyzed by ICP-MS at the Rutgers University Chemistry Department laboratory