State of Delaware
DEPARTMENT OF
NATURAL RESOURCES &
ENVIRONMENTAL CONTROL
Collin P. O'Mara, Secretary

Delaware's 2010 305(b) Groundwater-Quality Assessment Based on Public-Well Data

by Joshua W. Kasper[1]

2010

[1] Division of Water Resources, Water Supply Section, Groundwater Protection Branch

Contents

Figures

Figures (*cont.*)

Tables

Introduction

Per Section 106(e) of the Federal Water Pollution Control Act (FWPCA; as amended through P.L. 107-303, November 27, 2002), more commonly known as the Clean Water Act or CWA, States are required to collect, compile, and analyze water-quality data and report results to the U.S. Environmental Protection (U.S. EPA) on a biennial basis. Because reporting requirements are outlined in Section 305(b) of the FWPCA, these reports are commonly referred to as "305(b) reports." Although the FWPCA focuses on the quality of navigable [surface] waters, Section 106(e) of the FWPCA states that groundwater quality must be reported "…to the extent practicable." Guidelines to this end have consequently been developed (U.S. EPA, 1997).

Recent inter-Departmental policy for Delaware has improved the Department of Natural Resources and Environmental Control's (DNREC's) ability to assess statewide groundwater quality (DNREC, 2007). The referenced policy requires that all groundwater samples collected in Delaware be identified by well permit number or "DNREC ID." The DNREC ID is the only statewide numbering system unique to well permits issued in Delaware and, therefore, the primary means to obtain well-construction information (DNREC, 2007). Well-construction information, in conjunction with geographic data and hydrogeologic mapping, allows for determinations of aquifer or aquifer type, basic data that are critical to any groundwater-quality investigation.

Efforts by the Department of Health and Social Services (DHSS) have been underway to identify water-quality data for public wells by DNREC ID. Electronic water-quality data are stored in the DHSS's Safe Drinking Water Information System (SDWIS). DNREC's Source Water Assessment and Protection Program (SWAPP) maintains a database (hereafter the "SWAPP database") that contains DNREC IDs, well-construction details, geographic coordinates, and hydrogeologic data for public water-supply wells in Delaware. This 305(b) groundwater-quality assessment is based on information stored in SDWIS and the SWAPP database. Methodologies for data acquisition and analysis are similar to those employed in DNREC's 2008 305(b) groundwater-quality assessment (Kasper, 2008).

Purpose and scope

This report serves as "Part IV: Groundwater Assessment" of Delaware's overall 2010 305(b) report (DNREC, 2010). The primary purpose of this report is to summarize and report raw or apparently raw groundwater-quality data collected from public water-supply wells in Delaware during calendar years 2008 and 2009. Per U.S. EPA (1997) guidance, data are evaluated with respect to hydrogeologic setting and water-quality criteria where possible. The scope of this report is limited to available data obtained from two sources: the DHSS's SDWIS and the DNREC's SWAPP database.

Acknowledgements

Philippe Maitre of the DHSS is gratefully acknowledged for developing SDWIS queries to generate raw (or apparently raw) groundwater-quality data for public water-supply wells. Edward Hallock of the DHSS's Office of Drinking Water (ODW) also is thanked for his assistance with facilitating SDWIS data acquisition. Anne Mundel (DNREC) assisted with the acquisition of SWAPP data. John T. Barndt, P.G. and Scott A. Strohmeier, P.G. (both DNREC) reviewed the draft report and provided useful comments for its improvement.

General hydrogeology

Delaware covers ~2,010 mi^2 and is comprised of two Physiographic Provinces: the Piedmont and the Atlantic Coastal Plain. The Piedmont covers ~82 mi^2 in northern Delaware (Figure 1) and is comprised of meta-sedimentary, meta-igneous, and igneous rocks (Plank et al., 2000). Areally, metamorphic rocks (mostly gneiss) are dominant based on 1-36,000-scale mapping of bedrock geology in Delaware's Piedmont (Schenck et al., 2000). Bedrock ages range from Precambrian to Silurian, although diabase dikes of Mesozoic age have been identified (Plank et al., 2000; Schenck et al., 2000).

Two main hydrogeologic units have been recognized in Delaware's Piedmont (after Werkheiser, 1995): non-carbonate and carbonate aquifers. Werkheiser (1995) used the term "non-carbonate aquifer" to describe the hydrologic unit occurring predominantly in fractured gneiss. For the purpose of this reporting, however, "fractured-rock aquifer" is used so as to avoid confusion with other non-carbonate aquifers occurring in Coastal-Plain sediments (Table 1). This aquifer-type designation is generally consistent with the SWAPP database. The Cockeysville aquifer, which occurs in the Cockeysville Marble, is the only carbonate aquifer in Delaware. Although the outcrop of the Cockeysville Marble is relatively small (~2.2 mi^2), the Cockeysville aquifer is a major source of public and domestic water supply in northern Delaware (Talley, 1995; Werkheiser, 1995). In this report the term "karst aquifer" is used in lieu of carbonate or Cockeysville aquifer (Table 1). This aquifer-type designation is consistent with the SWAPP database.

The remaining 1,928 mi^2 (96%) of Delaware's land-surface area is underlain by Mid-Atlantic Coastal Plain sediments that onlap crystalline basement rocks (i.e., bedrock). These seaward-dipping and -thickening sediments range in age from Triassic to Holocene (Table 1). Depositional environments vary, but most sediments were laid down in marine, estuarine, and fluvial environments. Overall, 13 major and several minor aquifers are recognized in the Coastal Plain of Delaware (Table 1). Minor aquifers occur mostly in Miocene-age sediments (Table 1) and hence the name "minor-Miocene aquifers" has been used to designate these hydrologic units.

For the purpose of this reporting, Coastal-Plain aquifers are subdivided into three main aquifer types: unconfined, semi-confined, and confined. These aquifer-type designations are consistent with the SWAPP database. The unconfined aquifer, also called the Columbia aquifer, occurs predominantly in Pleistocene- to Pliocene-age sediments that comprise Delaware's surficial geologic framework (Table 1). (The term "unconfined aquifer" is used in this report in lieu of "Columbia aquifer" because, as indicated in Table 1, the Columbia aquifer may be confined in some locations.) In areas where confined aquifers subcrop, however, the unconfined aquifer can be in direct hydraulic connection with older geologic units. The semi-confined and confined aquifers predominantly occur in sediments of Miocene age or older. In general, Miocene aquifers (Table 1) are tapped for potable water supply in Kent County and Sussex County; Eocene and Paleocene aquifers (Table 1) are tapped in southern New Castle County and Kent County; and Cretaceous aquifers (Table 1) are tapped in New Castle County.

Methods of investigation

Groundwater quality in Delaware was assessed based on pre-existing information stored in two separate databases: the DHSS's SDWIS and the DNREC's SWAPP database. DHSS staff developed queries to extract SDWIS records of raw or apparently raw groundwater-quality data collected from public water-supply systems during the reporting period (2008-09). Data resulting from these queries (53,141 analyses) were provided to DNREC in an April 6, 2010 Microsoft Office Access 2007 ("Access") database. Records obtained from the SWAPP database were current as of April 13, 2010. The records included well details such as DNREC ID, depth, geographic coordinates, geologic formation, aquifer, and aquifer type.

Access was used to link and extract data from SDWIS and the SWAPP database. For wells with more than one analysis of a given analyte, results were averaged. Analytes not detected above laboratory quantitation limits ("nondetects") were treated as zeros in all calculations. Results were evaluated with respect to Primary Maximum Contaminant Levels (PMCLs), Secondary Maximum Contaminant Levels (SMCLs), and Health Advisories (HAs) for public water-supply systems (DHSS, 2005; U.S. EPA, 2009). Hardness data were evaluated with respect to the scale of Love (1962). Because only raw or apparently raw groundwater-quality data were evaluated, the results may not be representative of finished or treated water delivered to consumers. Therefore, an exceedence of a drinking-water standard does not necessarily indicate that a public water-supply system is not in compliance (see also Ferrari, 2001, p. 5).

Where possible, data were evaluated with respect to aquifer type (i.e., unconfined, confined, semi-confined, fractured-rock, or karst). Data were, however, generally insufficient in quantity for meaningful analyses of groundwater quality in specific aquifers (Table 1). Some data also were evaluated with respect to sample depth, which was taken to be the bottom of a well's screened interval. Evaluation of trends (e.g., concentration vs. depth) in this assessment are qualitative and not statistically derived. Environmental Systems Research Institute's (ESRI's) ArcView version 3.2 ("ArcView"), a geographic information system (GIS), was used for the spatial analysis of groundwater data. Tabulated statistics (e.g., Table 2) are the result Microsoft Office Excel 2007 ("Excel") calculations. Golden Software, Inc.'s Grapher version 5.01 ("Grapher") was used to construct percentile diagrams. Outliers shown on percentile diagrams (e.g., Figure 4) are computed by Grapher using the following equations:

$$QL - 1.5 \times IQR \quad \text{or} \quad QU - 1.5 \times IQR$$

Where:

IQR is the interquartile range (i.e., the difference between the 75^{th} and 25^{th} percentiles)
QL is the lower quartile or 25^{th} percentile (i.e, the bottom of the box in Figure 4)
QU is the upper quartile or 75^{th} percentile (i.e., the top of the box in Figure 4)

Differences between tabulated statistics (e.g., Table 2) and corresponding percentile diagrams (e.g., Figure 4) are the result of differences in the computational methods of Excel and Grapher.

Table 1. List of major and minor aquifers in Delaware (modified after the Delaware Geological Survey, http://www.dgs.udel.edu/Hydrology/Hydrostrat.aspx, accessed June 16, 2010).

AGE	GEOLOGIC UNITS	HYDROLOGIC UNITS
Holocene	various informal deposits	Unassigned
Pleistocene	Carolina Bay deposits	Columbia aquifer
	upland bog deposits	
	Cypress Swamp Fm.	
	Nanticoke deposits	
	Scotts Corners Fm.	
	Lynch Heights Fm.	
	Omar Fm.	Confining beds / minor poor aquifer
	Columbia Fm.	Columbia aquifer
Pliocene	Beaverdam Fm.	
Miocene	Bethany Fm.	Pocomoke aquifer and confining beds
	Cat Hill Fm.	Manokin aquifer and confining beds
	St. Marys Fm.	Confining beds / minor poor aquifer
	Choptank Fm.	unnamed aquifers and confining beds
		Milford aquifer
	Calvert Fm.	Confining bed
		Frederica aquifer
		Confining bed
		Federalsburg aquifer
		Confining bed
		Cheswold aquifer
		Confining bed
Oligocene	glauconitic unit	Unassigned
Eocene	glauconitic unit	
	Piney Point Fm.	Piney Point aquifer and confining beds
	Shark River Fm.	Confining beds
	Deal Fm.	
	Manasquan Fm.	Rancocas aquifer and confining beds
Paleocene	Vincentown Fm.	
	Hornerstown Fm.	Confining beds
Cretaceous	Navesink Fm.	
	Mount Laurel Fm.	Mount Laurel aquifer
	Marshalltown Fm.	Confining bed
	Englishtown Fm.	Englishtown aquifer
	Merchantville Fm.	Confining bed
	Magothy Fm.	Magothy aquifer
	Potomac Fm.	Potomac aquifer system and confining beds
Triassic and Jurassic	Post-rift unconformity rocks (of Jurassic age) and rift-basin rocks (inferred)	Unassigned
Paleozoic to Precambrian	Various Fms. (bedrock)	Fractured-rock aquifer
		Cockeysville (karst) aquifer

Public wells

As of April 13, 2010, there were 1,121 active (and 392 inactive or unassigned) public water-supply wells in the SWAPP database. Of the active wells, 1,095 (97%) have geographic coordinates and are plotted in Figure 1A. With reference to Figure 1A, there are 244 wells (22%) in New Castle County, 296 wells (27%) in Kent County, and 555 wells (51%) in Sussex County. (Percentages may not total 100% due to rounding.)

Aquifer type is known for 942 (84%) of the 1,121 active wells (Figure 2). Wells where aquifer type is known and geographic coordinates are available are plotted in Figures 1B thru 1F. Out of all active wells, Coastal-Plain wells account for 876 (78%) and Piedmont wells account for 66 (6%) (Figure 2). The large percentage of Coastal-Plain wells relative to Piedmont wells is due to both land-area differences and the fact that public-water supply in the Piedmont and New Castle County is largely from surface-water resources (Wheeler, 2003). Aquifer type for the remaining 179 active wells is either unknown (due to a lack of well-construction data) or not yet assigned (Figure 2).

Coastal-Plain wells include wells screened in unconfined, semi-confined, or confined aquifers (Figures 1B thru 1D and Figure 2). Out of the 876 Coastal-Plain wells, unconfined wells account for 403 (36%), confined wells account for 423 (38%), and semi-confined wells account for 50 (4%) (Figure 2). A large majority of the unconfined wells with geographic coordinates (320 of 403 or 79%) are located in Sussex County; the remaining unconfined wells include 45 (11%) in Kent County and 37 (9%) in New Castle County (Figure 1B). Confined wells are more evenly distributed throughout the Coastal Plain of Delaware, with most of the wells situated in Kent County (Figure 1C). Specifically, out of 421 confined wells with geographic coordinates, 174 (41%) are located in Kent County, 132 (31%) are located in New Castle County, and 115 (27%) are located in Sussex County. All 50 semi-confined wells have geographic coordinates (Figure 1D); 26 (52%) are located in Kent County, 16 (32%) are located in Sussex County, and 8 (16%) are located in New Castle County.

Piedmont wells include fractured-rock and karst wells and are limited to only the northernmost portion of the State (Figures 1E and 1F and Figure 2). Out of the 66 Piedmont wells, fractured-rock wells account for 57 (86%) and karst wells account for 9 (14%) (Figure 2). All 57 fractured-rock and 9 karst wells (Figure 2) have geographic coordinates and are plotted in Figures 1E and 1F, respectively. Karst wells are coincident with the Cockeysville Marble outcrop in northern New Castle County (Figure 1F).

Well depths, taken as the bottom of the well screen, are known for 1,022 (91%) of 1,121 active wells (Figure 3). Overall, well depths range from 22 to 957 ft below land surface (bls) and are skewed (Figure 3). The median well depth is 135 ft bls and the 25th and 75th percentiles are 87.25 and 235 ft bls, respectively. Well depths are not known for 99 (9%) of the active wells (Figure 3).

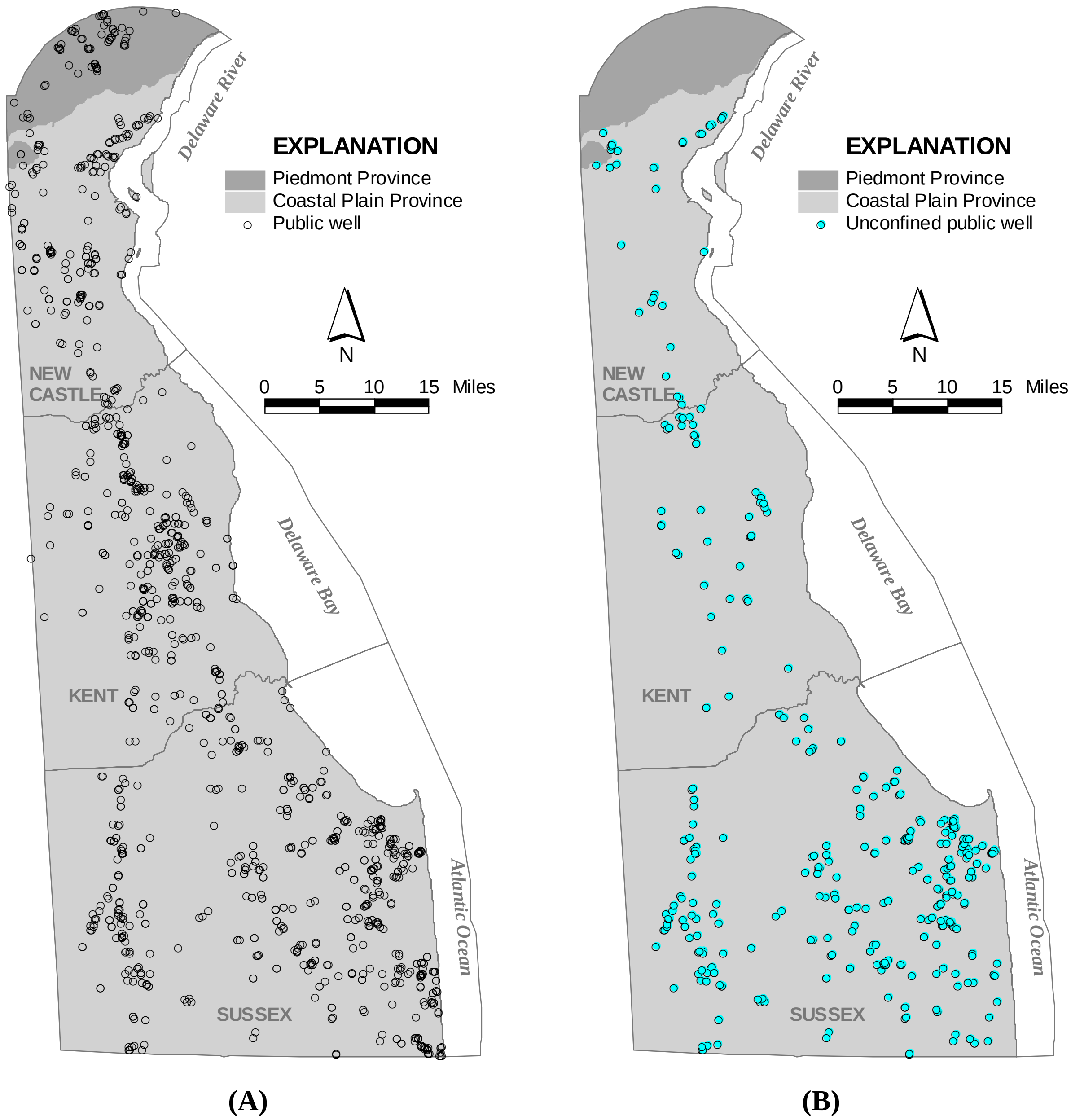

Figure 1. Maps of active public water-supply wells in Delaware – (A) all wells and (B) unconfined wells.

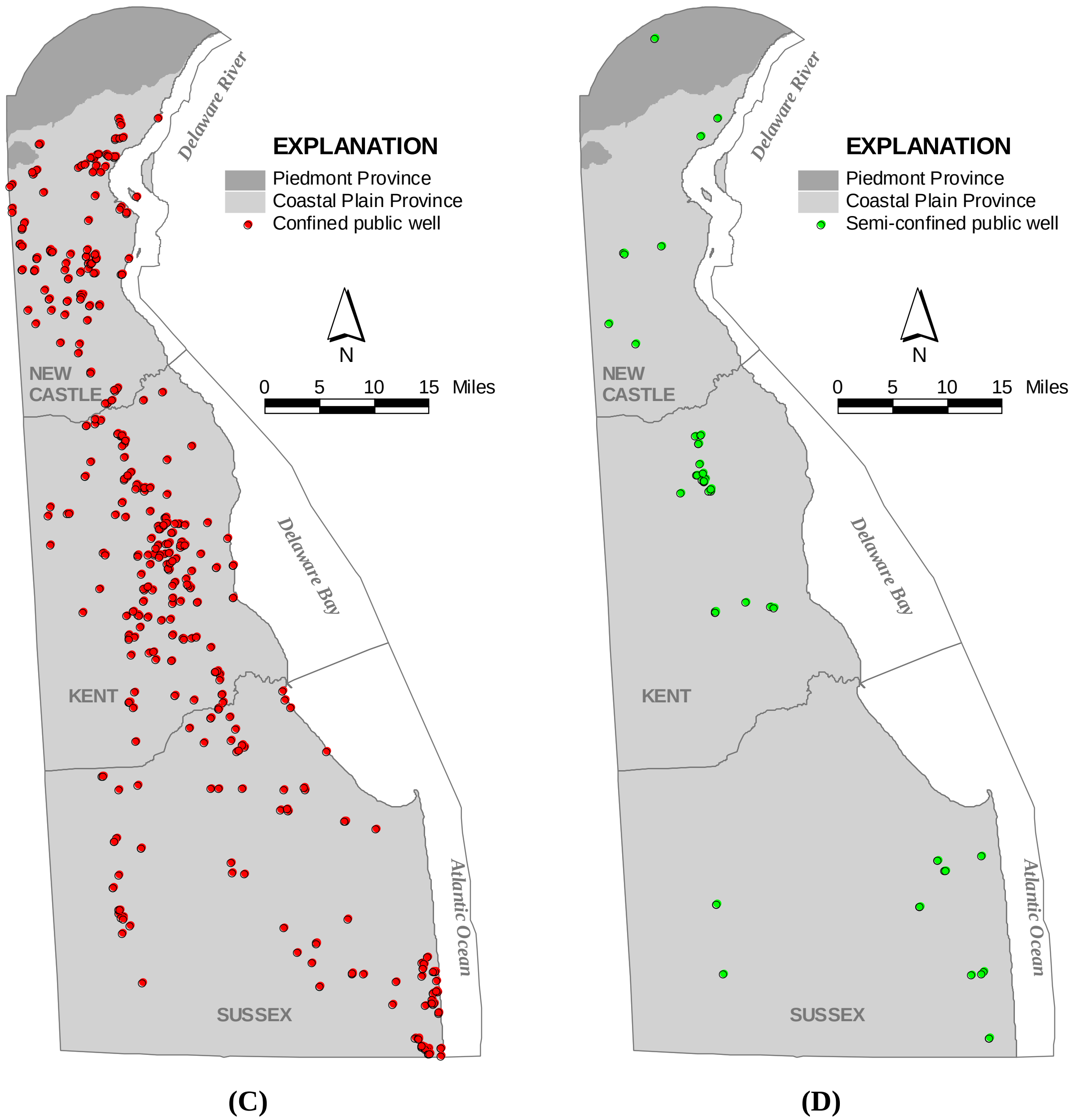

Figure 1. Maps of active public water-supply wells in Delaware (*cont.*) – (C) confined wells and (D) semi-confined wells.

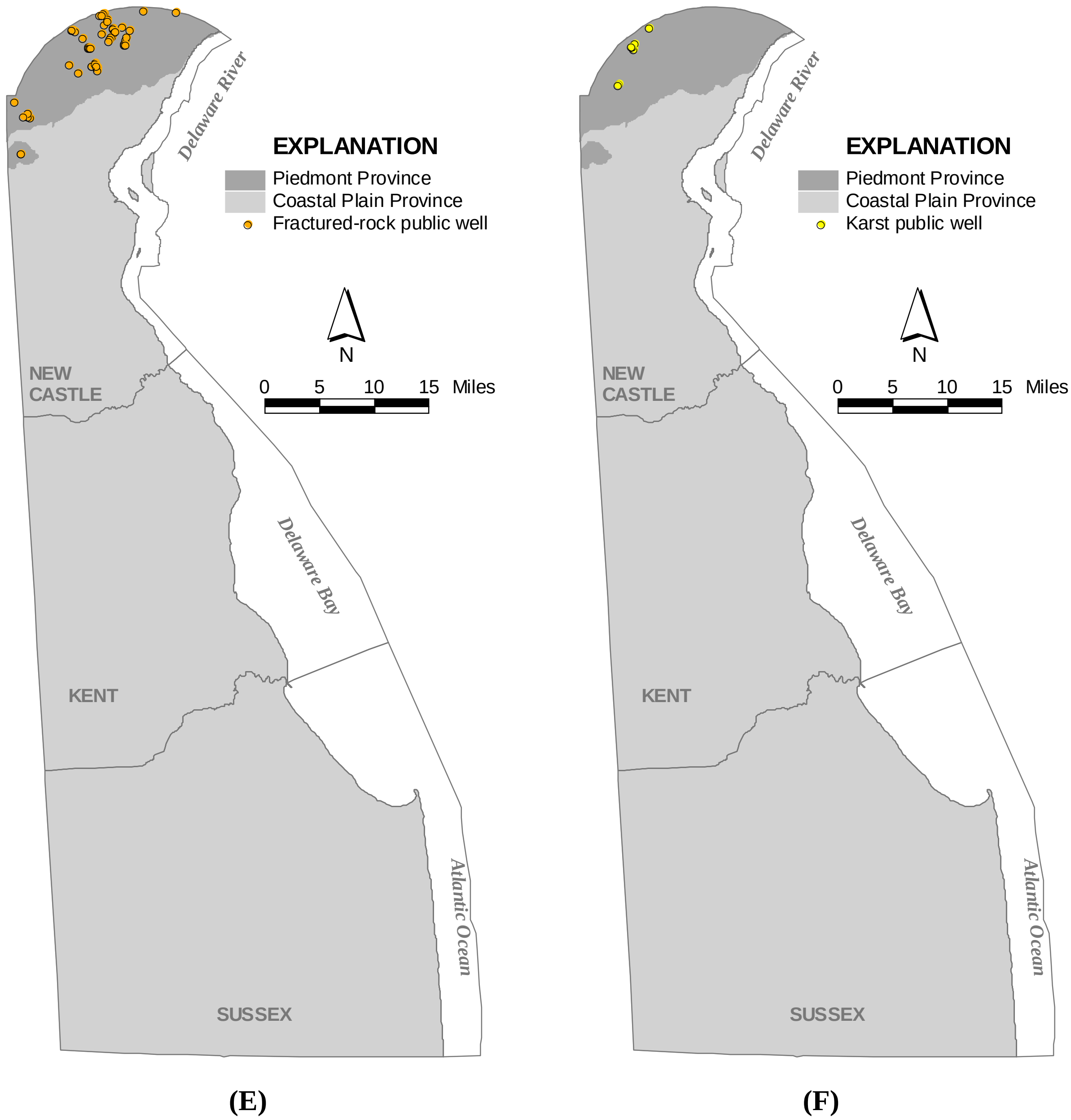

Figure 1. Maps of active public water-supply wells in Delaware (*cont.*) – (E) fractured-rock wells and (F) karst wells.

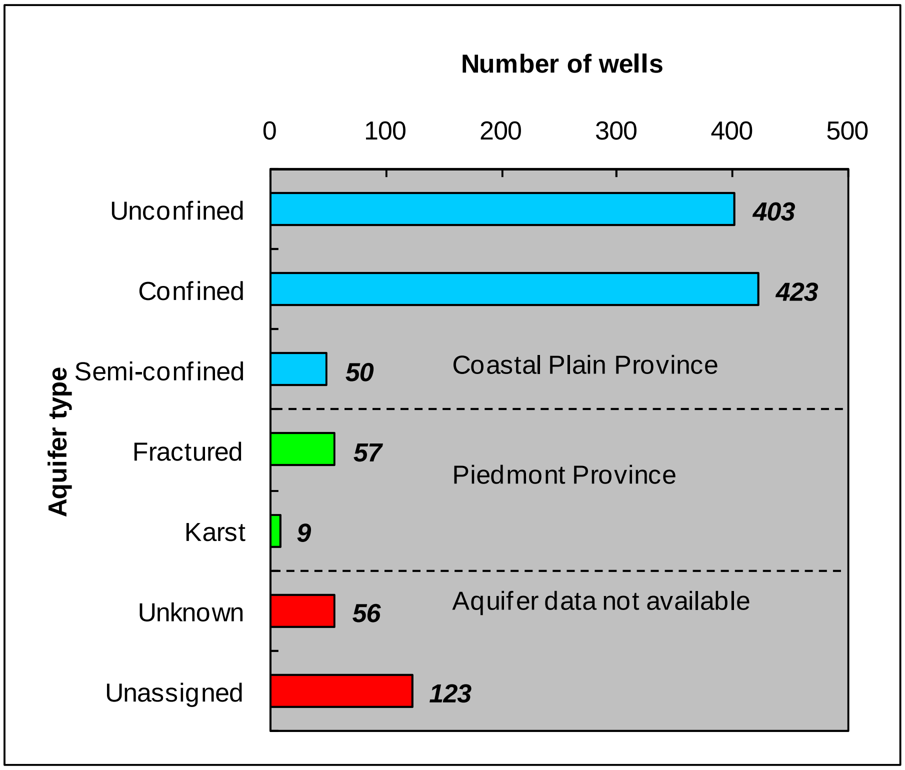

Figure 2. Histogram of active public water-supply wells by aquifer type.

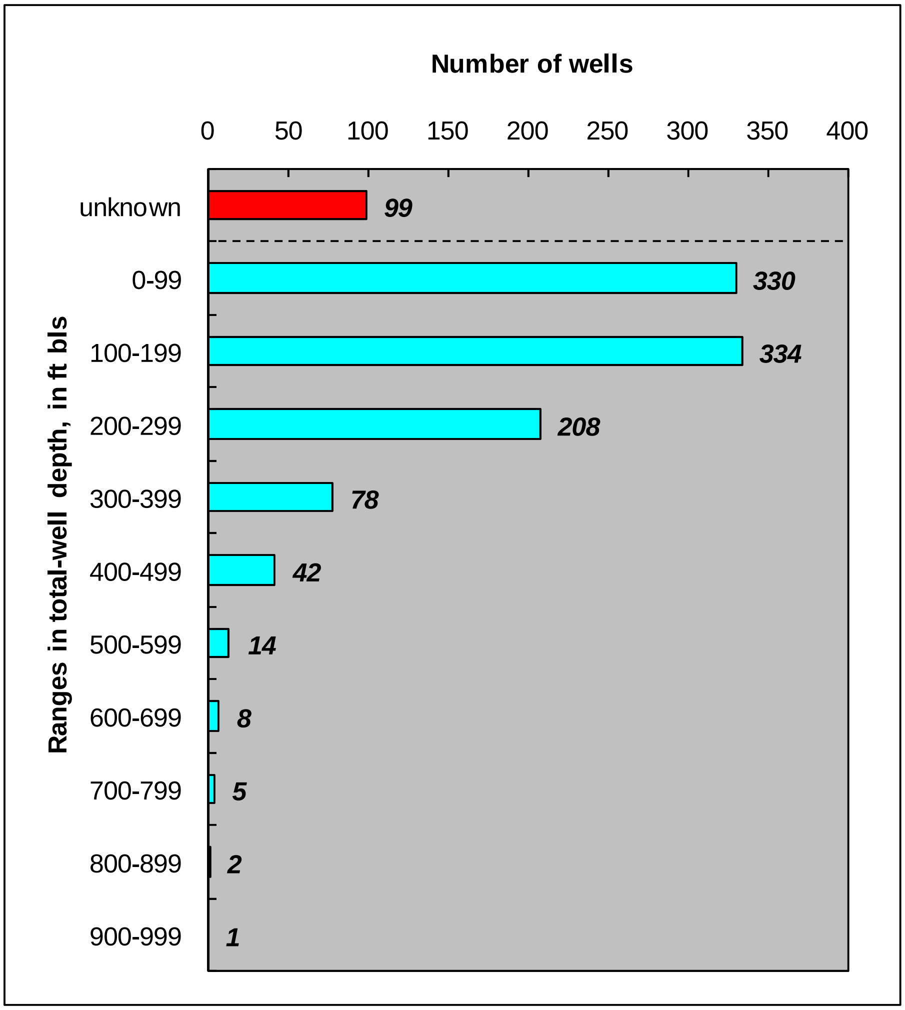

Figure 3. Histogram of active public water-supply wells by ranges in total-well depth.

Results and discussion

Results are grouped into four main categories: general chemistry, organic compounds, trace elements, and radionuclides.

General chemistry

For this assessment, general groundwater chemistry includes parameters routinely measured in public water-supply systems. Nitrate as nitrogen is the only parameter in this category with a PMCL (10 mg/L; U.S. EPA, 2009). Other parameters in this category include those that generally affect the aesthetic qualities of the water supply, such as taste, odor, color, corrosiveness, etc. Most of these parameters have SMCLs.

Nitrate as nitrogen

Overall, 1,503 nitrate as nitrogen ("nitrate") analyses are in the SDWIS query provided to DNREC. Of these, 410 (27%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 231 nitrate analyses where aquifer type is known (Table 2). This number translates to ~25% of the total number of wells (942) where aquifer type is known (Figure 2). Overall, nitrate concentrations ranged from nondetectable to 24 mg/L with a median value of 1 mg/L (Table 2 and Figure 4). Nitrate was not detected above the laboratory quantitation limit in 103 (45%) of the 231 analyses (Table 2). Concentrations in 124 (54%) of the samples exceeded 0.4 mg/L (Table 2), a threshold used to distinguish between natural and human-impacted groundwater (Hamilton et al., 1993). Nitrate concentrations exceeded the PMCL (10 mg/L) in 15 (6%) of the 231 samples (Table 2). All but one of the PMCL exceedences occurred in Sussex County; the remaining exceedence occurred in southern Kent County (Figure 5). Overall, nitrate concentrations decrease with depth and, below depths of ~200 ft bls, nitrate concentrations were below the PMCL (Figure 6). Concentrations exceed 0.4 mg/L to depths of ~400 ft bls, however, and this may be an indication of the vertical extent of human influence on groundwater quality.

Unconfined wells account for 114 (49%) of the 231 individual samples linked by DNREC ID (Table 2). This number translates to ~28% of the total number of active unconfined wells (403) statewide (Figure 2). Nitrate was not detected above the laboratory quantitation limit in 19 (17%) of the 114 samples. Concentrations in 93 (82%) of the 114 samples exceeded 0.4 mg/L suggesting that the groundwater quality in the unconfined aquifer is largely affected by human activities. The cluster of concentrations below 0.4 mg/L in the southeastern portion of Sussex County coincides with an area where groundwater is largely anoxic (Figure 5a; Kasper and Strohmeier, 2007). The most elevated nitrate concentration (24 mg/L) was detected in an unconfined well (Table 2 and Figure 4). Out of the five aquifer types, unconfined wells had the highest median nitrate concentration (3.79 mg/L) and the second-lowest percentage of nondetects (Table 2). The median concentration is lower than the median concentration (5.2 mg/L) from a USGS study of 30 randomly-selected unconfined public water-supply wells in Delaware (Ferrari, 2002). Moreover, the median nitrate concentration from this study is lower than the median concentrations for shallow (5.4 mg/L) and intermediate (5.5 mg/L) depths in the unconfined aquifer on the Delmarva Peninsula (Denver et al., 2004). A watershed-scale study in Sussex County, Delaware, reported a higher median nitrate concentration (6.4 mg/L) for the unconfined aquifer (Kasper and Strohmeier, 2007). Land use in that watershed is and has been largely agricultural. For this assessment, nitrate exceeded the PMCL in 12 (11%) of the 114 unconfined aquifer samples, and each of the exceedences occurred in Sussex County (Figure 5a). This percentage of PMCL exceedences is higher than the percentage reported by Ferrari (2001), who found one in 30 public wells with nitrate above the PMCL. In contrast, other recent studies of shallow groundwater quality at the State scale (Pellerito et al., 2008) and watershed scale (Kasper and Strohmeier, 2007) reported higher percentages of PMCL exceedences (18 and 32%, respectively). There is no apparent trend in nitrate concentrations with depth in the unconfined aquifer (Figure 6). The most elevated concentration (24 mg/L) was detected at a depth of 81 ft bls; the deepest PMCL exceedence (12.3 mg/L) occurred at a depth of 148 ft bls. Nitrate concentrations were below the PMCL in the 14 unconfined wells shallower than 60-ft deep.

Confined wells account for 95 (41%) of the 231 individual samples linked by DNREC ID (Table 2). This number translates to ~22% of the total number of active confined wells (423) statewide (Figure 2). Nitrate was not detected above the laboratory quantitation limit in 80

(84%) of the 95 samples. However, concentrations in 14 (15%) of the 95 wells exceeded 0.4 mg/L suggesting that the groundwater quality in a considerable fraction of confined aquifer wells may be susceptible to human activities. Of these, 9 are confined Potomac aquifer wells located in the northernmost portion of the Coastal Plain (Figure 5b). Nitrate exceeded the PMCL in 1 (1%) of the 95 samples suggesting either localized or poor confinement and (or) compromised well construction (Table 2). The single PMCL exceedence occurred in a 195-ft deep well located southern Kent County (Figure 5b). Nitrate concentrations generally decrease with depth in confined aquifers, consistent with the overall trend (Figure 6).

Semi-confined wells account for 12 (5%) of the 231 individual samples linked by DNREC ID (Table 2). This number translates to ~24% of the total number of active semi-confined wells (50) statewide (Figure 2). Nitrate was not detected above the laboratory quantitation limit in 3 (25%) of the 12 samples. Limited data suggest that semi-confined wells have an intermediate susceptibility to human impacts relative to confined and unconfined wells (Table 2). Specifically, nitrate concentrations in a large fraction of the semi-confined well samples (67%) exceeded 0.4 mg/L, indicating the potential for human influence on groundwater quality. Moreover, two (17%) of the 12 wells had nitrate above the PMCL, with one result over two times the PMCL (23 mg/L; Table 2). Both of these wells are located in Sussex County (Figure 6).

Fractured-rock wells account for 3 (~1%) of the 231 individual samples linked by DNREC ID (Table 2). This number translates to ~5% of the total number of fractured-rock wells (57) statewide (Figure 2). Although data are extremely limited, nitrate concentrations in 2 of the 3 fractured-rock well samples exceeded 0.4 mg/L. None of the nitrate concentrations, however, exceeded the PMCL.

Karst wells account for 7 (~3%) of the 231 individual wells/samples linked by DNREC ID (Table 2). This number translates to ~78% of the total number of karst wells (9) statewide (Figure 2). Nitrate was detected in 100% of the samples and concentrations always exceeded 0.4 mg/L. Karst wells also had the second-highest median nitrate concentration (3.22 mg/L; Table 2), but none of the concentrations exceeded the PMCL. There is no discernable trend in nitrate versus depth for Karst wells based on available data (Figure 6).

Table 2. Statistical summary of nitrate data by aquifer type. [mg/L, milligrams per liter; ND, not detected; ---, no data; PMCL, primary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2009).]

STATISTICS	ALL WELLS	UNCONFINED WELLS	CONFINED WELLS	SEMI-CONFINED WELLS	FRACTURED-ROCK WELLS	KARST WELLS
Number of wells/samples (#)	231	114	95	12	3	7
Percent of total (%)	100	49	41	5	1	3
Maximum (mg/L)	24.00	24.00	12.80	23.00	3.10	5.81
75th percentile (mg/L)	4.60	6.71	0.00	7.98	2.85	4.02
50th percentile (mg/L)	1.00	3.79	0.00	1.45	2.60	3.22
25th percentile (mg/L)	0.00	1.20	0.00	0.14	1.30	2.28
Minimum (mg/L)	0.00	0.00	0.00	0.00	0.00	2.18
Number not detected (#ND)	103	19	80	3	1	0
Percent not detected (%ND)	45	17	84	25	33	0
Number > 0.4 mg/L (#)	124	93	14	8	2	7
Percent > 0.4 mg/L (%)	54	82	15	67	67	100
Number > 10 mg/L PMCL (#)	15	12	1	2	0	0
Percent > 10 mg/L PMCL (%)	6	11	1	17	0	0

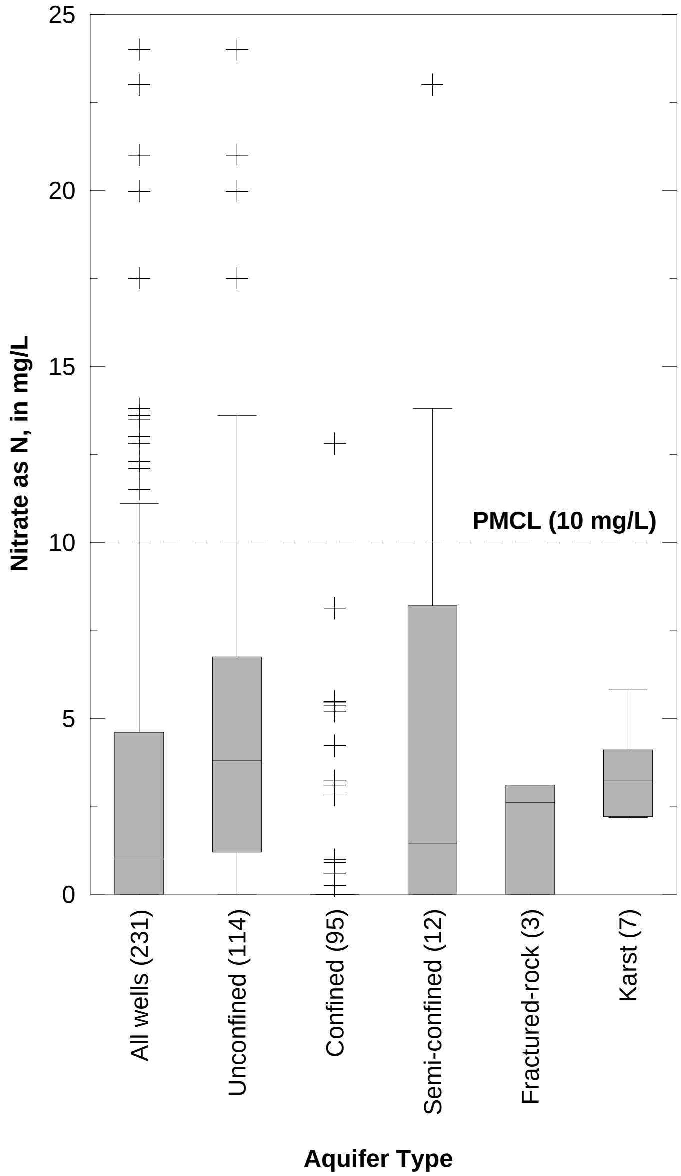

Figure 4. Percentile diagrams of nitrate data by aquifer type. [mg/L, milligrams per liter; crosses, outliers; (#), number of samples; PMCL, primary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2009).]

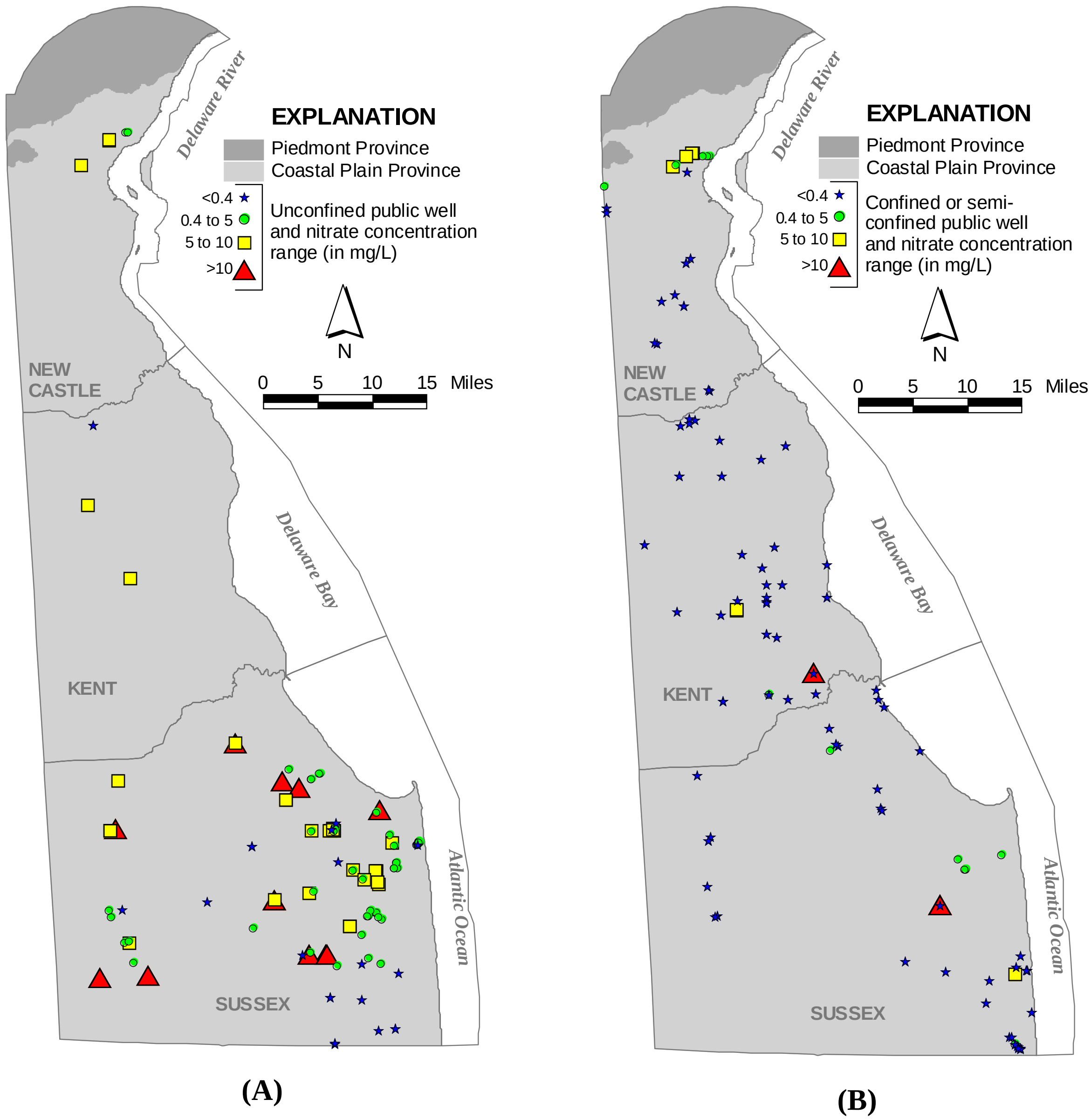

Figure 5. Maps showing nitrate concentration ranges in (A) unconfined and (B) confined and semi-confined public water-supply wells.

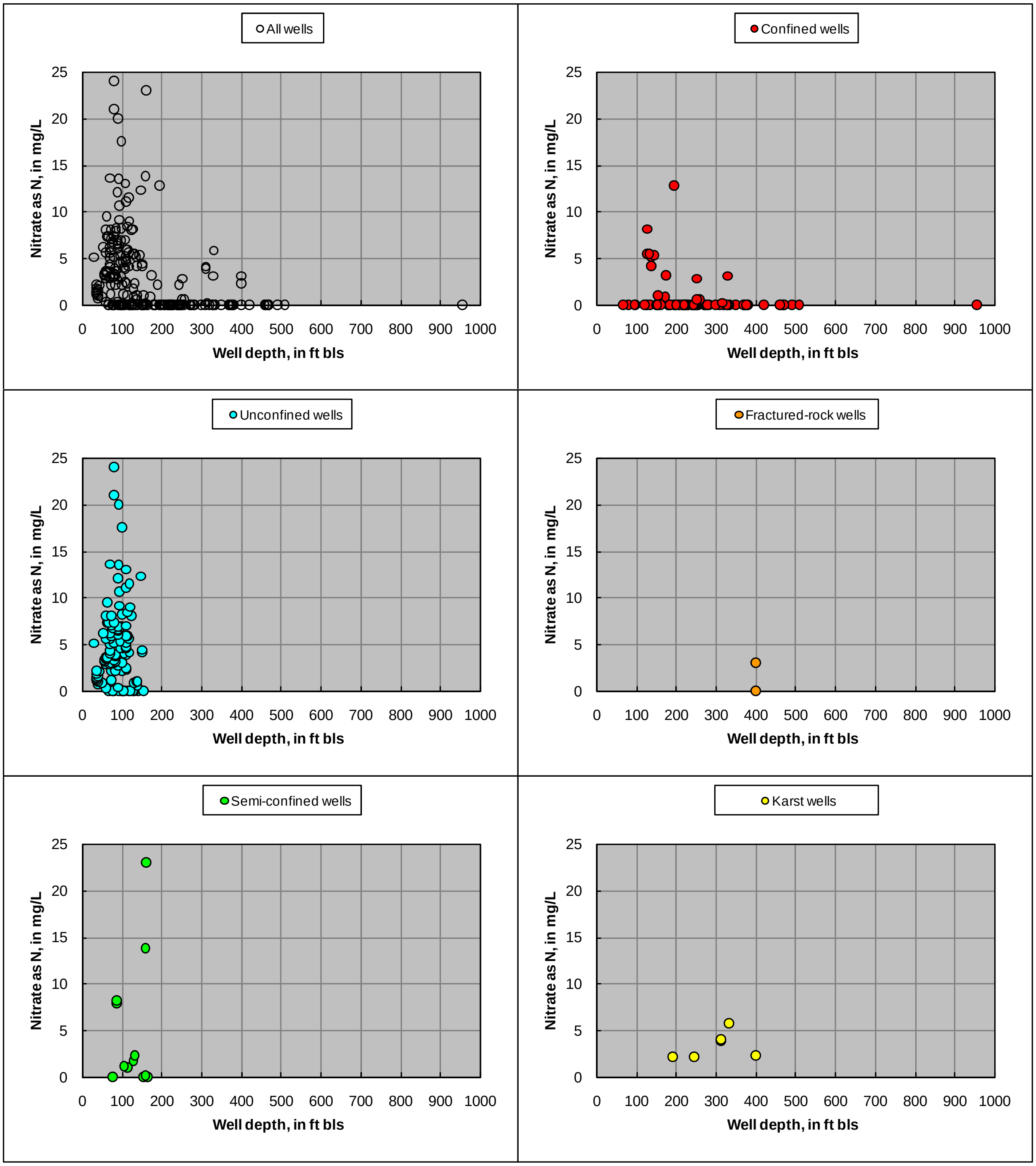

Figure 6. Scatter plots of nitrate versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface.]

Total dissolved solids

Overall, 708 total dissolved solids (TDS) analyses are in the SDWIS query provided to DNREC. Of these, 360 (51%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 216 TDS analyses where aquifer type is known (Table 3). This number translates to ~23% of the total number of wells (942) where aquifer type is known (Figure 2). Overall, TDS concentrations ranged from 24 to 472 mg/L with a median value of 154 mg/L (Table 3 and Figure 7). TDS concentrations never exceeded the SMCL (500 mg/L), although this value was approached in a confined well (472 mg/L; Table 3).

Although data are limited, karst wells had the highest median TDS concentration (416 mg/L; Table 3 and Figure 7). TDS data for karst and fractured-rock wells were in sharp contrast, a finding that is consistent with Werkheiser (1995). Elevated TDS in karst wells has been attributed to the dissolution of carbonate rocks (Werkheiser, 1995). Based on 109 samples, unconfined wells had the lowest median TDS concentration (136 mg/L; Table 3 and Figure 7), a value that agrees in general with Ferrari's (2001) median (116 mg/L). The median TDS concentrations for confined and semi-confined wells (198 and 159 mg/L, respectively) were higher than the median for unconfined wells. Relatively higher TDS concentrations for the confined and semi-confined aquifers are likely due to longer groundwater contact time with formation sediments. Although TDS generally increases with depth, elevated concentrations can be found at shallower depths (Figure 8).

Table 3. Statistical summary of total dissolved solids (TDS) data by aquifer type. [mg/L, milligrams per liter; SMCL, secondary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2009).]

STATISTICS	ALL WELLS	UNCONFINED WELLS	CONFINED WELLS	SEMI-CONFINED WELLS	FRACTURED-ROCK WELLS	KARST WELLS
Number of wells/samples (#)	216	109	88	9	3	7
Percent of total (%)	100	50	41	4	1	3
Maximum (mg/L)	472	444	472	214	188	443
75th percentile (mg/L)	220	160	232	186	164	428
50th percentile (mg/L)	154	136	198	159	140	416
25th percentile (mg/L)	116	98	153	92	114	286
Minimum (mg/L)	24	26	24	74	88	168
Number not detected (#ND)	0	0	0	0	0	0
Percent not detected (%ND)	0	0	0	0	0	0
Number > 500 mg/L SMCL (#)	0	0	0	0	0	0
Percent > 500 mg/L SMCL (%)	0	0	0	0	0	0

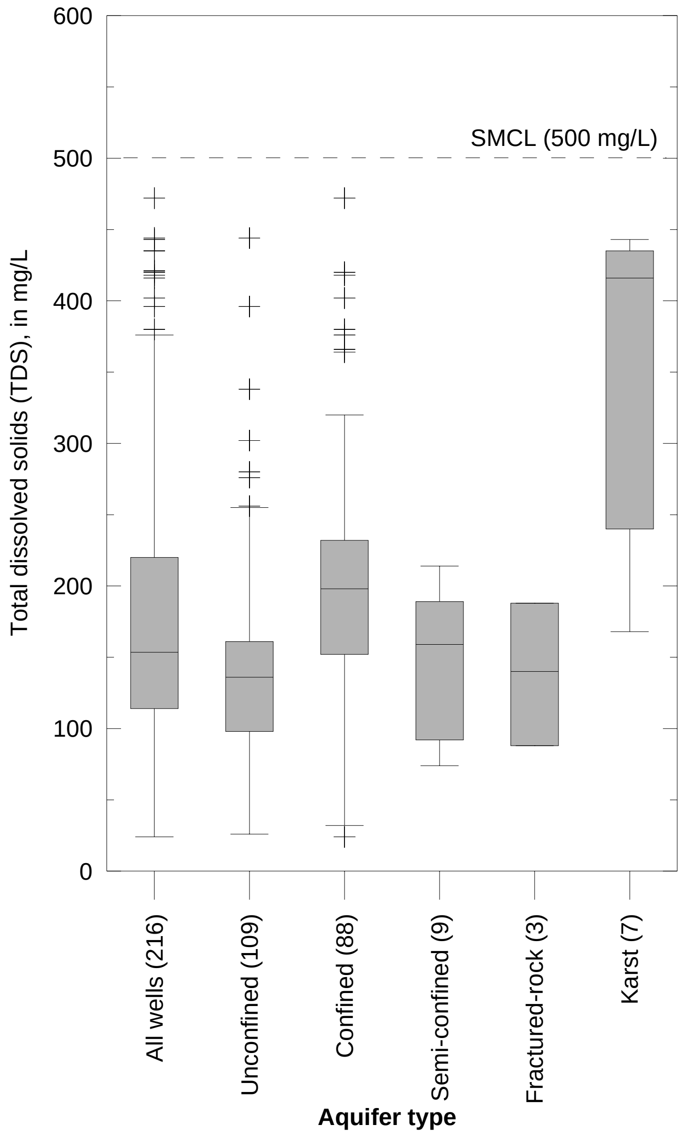

Figure 7. Percentile diagrams of total dissolved solids (TDS) data by aquifer type. [mg/L, milligrams per liter; crosses, outliers; (#), number of samples; SMCL, secondary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2009).]

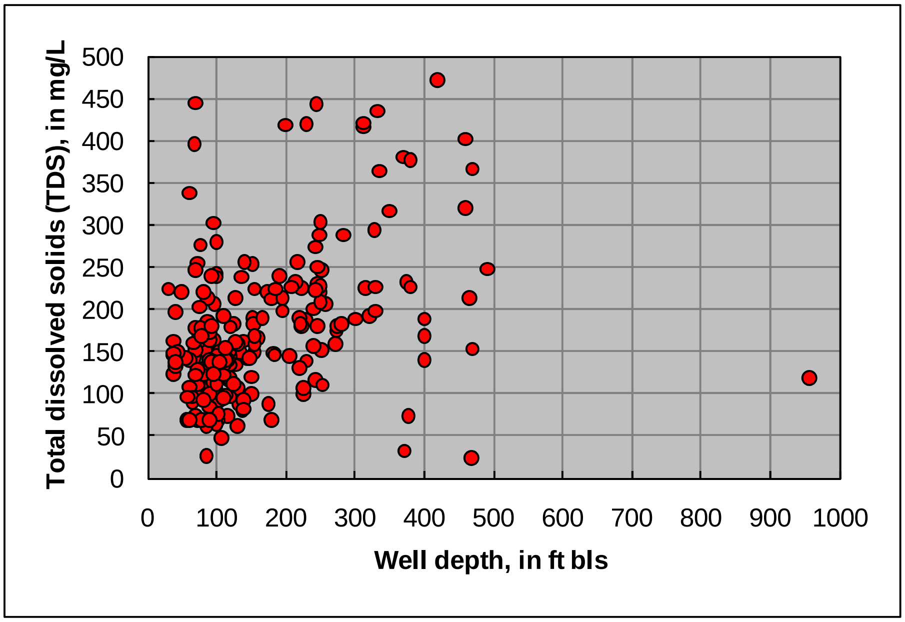

Figure 8. Scatter plot of total dissolved solids (TDS) versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface.]

Chloride

Overall, 957 chloride analyses are in the SDWIS query provided to DNREC. Of these, 386 (40%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 222 chloride analyses where aquifer type is known (Table 4). This number translates to ~24% of the total number of wells (942) where aquifer type is known (Figure 2). Overall, chloride concentrations ranged from 0.7 to 222 mg/L with a median value of 14.0 mg/L (Table 4 and Figure 9). Chloride concentrations never exceeded the SMCL (250 mg/L; Table 4).

Karst wells had the highest median chloride concentration (39.4 mg/L; Table 4 and Figure 9), consistent with the TDS results discussed previously. The most elevated chloride concentrations, however, were associated with unconfined wells. Specifically, all of the chloride concentrations above 100 mg/L in Figure 10 are associated with unconfined well samples. Unconfined and fractured-rock wells had the second- and third-highest median chloride concentrations (16.3 and 15.0 mg/L, respectively), although data for fractured-rock wells are extremely limited. These results may be indicative of impacts from human activities occurring at or near the land surface (e.g., road salting). The median value for the unconfined aquifer is in general agreement with Ferrari's (2001) median (18.3 mg/L). Semi-confined and confined wells had the lowest median chloride concentrations (9.8 and 6.4 mg/L, respectively). Overall, there is a decreasing trend in chloride with depth (Figure 10).

Table 4. Statistical summary of chloride data by aquifer type. [mg/L, milligrams per liter; SMCL, secondary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2009).]

STATISTICS	ALL WELLS	UNCONFINED WELLS	CONFINED WELLS	SEMI-CONFINED WELLS	FRACTURED-ROCK WELLS	KARST WELLS
Number of wells/samples (#)	222	111	92	9	3	7
Percent of total (%)	100	50	41	4	1	3
Maximum (mg/L)	222.0	222.0	89.7	39.9	16.5	49.0
75th percentile (mg/L)	26.5	28.0	19.8	16.4	15.8	43.3
50th percentile (mg/L)	14.0	16.3	6.4	9.8	15.0	39.4
25th percentile (mg/L)	7.9	12.6	2.3	9.1	10.6	25.9
Minimum (mg/L)	0.7	6.0	0.7	2.1	6.2	10.1
Number not detected (#ND)	0	0	0	0	0	0
Percent not detected (%ND)	0	0	0	0	0	0
Number > 250 mg/L SMCL (#)	0	0	0	0	0	0
Percent > 250 mg/L SMCL (%)	0	0	0	0	0	0

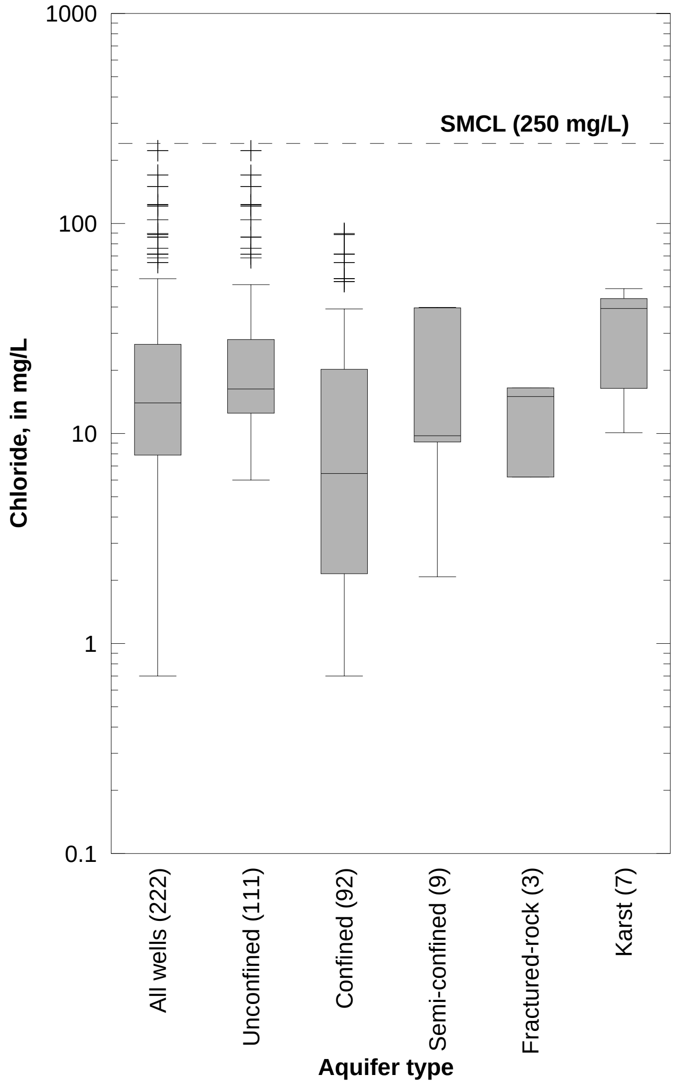

Figure 9. Percentile diagrams of chloride data by aquifer type. [mg/L, milligrams per liter; crosses, outliers; (#), number of samples; SMCL, secondary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2009).]

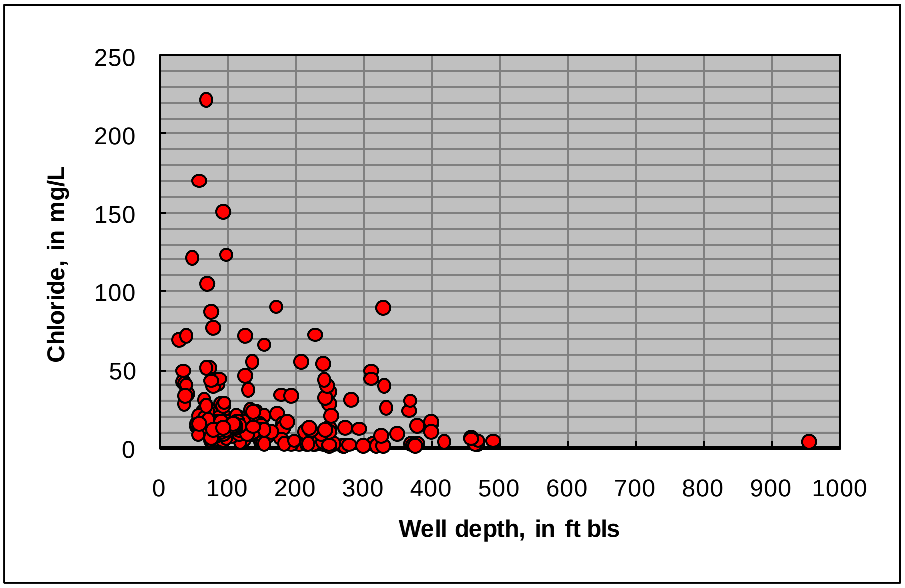

Figure 10. Scatter plot of chloride versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface.]

Sodium

Overall, 934 sodium analyses are in the SDWIS query provided to DNREC. Of these, 369 (40%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 220 sodium analyses where aquifer type is known (Table 5). This number translates to ~23% of the total number of wells (942) where aquifer type is known (Figure 2). Overall, sodium concentrations ranged from nondetectable to 158 mg/L with a median value of 10.9 mg/L (Table 5 and Figure 11). Sodium concentrations exceeded the HA (20 mg/L) in 55 (25%) of the 220 samples (Table 5).

Unconfined wells had the highest median sodium concentration (11.4 mg/L; Table 5 and Figure 11). The median value for the unconfined aquifer is in agreement with Ferrari's (2001) median (11.7 mg/L). Unconfined wells also had the second-largest fraction of concentrations above the HA (22%; Table 5 and Figure 11). Sodium is a component of the human diet and poultry manure and, therefore, its presence in shallow aquifers can reflect impacts from wastewater-disposal and agricultural practices (Denver, 1989). Confined and semi-confined wells had relatively lower median sodium concentrations (10.2 and 8.8 mg/L, respectively). Confined aquifers, however, had the highest sodium concentrations overall (up to 158 mg/L) and the largest fraction of concentrations above the HA (33%; Table 5 and Figure 11). In some instances, elevated sodium concentrations can be detected in glauconitic aquifers (e.g., the Piney Point aquifer) due to ion-exchange processes (Spoljaric, 1986). Sodium concentrations never exceeded the HA in karst or fractured-rock wells; however, at only 3 samples, data are limited for fractured-rock wells. Overall, there is no apparent trend in sodium with depth; sodium exceeded the HA at virtually all depths (Figure 12).

Table 5. Statistical summary of sodium data by aquifer type. [mg/L, milligrams per liter; HA, health advisory (U.S. EPA, 2009).]

STATISTICS	ALL WELLS	UNCONFINED WELLS	CONFINED WELLS	SEMI-CONFINED WELLS	FRACTURED-ROCK WELLS	KARST WELLS
Number of wells/samples (#)	220	110	91	9	3	7
Percent of total (%)	100	50	41	4	1	3
Maximum (mg/L)	158.0	138.0	158.0	21.0	10.4	16.8
75th percentile (mg/L)	19.8	17.7	27.7	13.7	10.4	12.9
50th percentile (mg/L)	10.9	11.4	10.2	8.8	10.4	9.9
25th percentile (mg/L)	8.6	8.9	8.0	7.9	6.5	5.9
Minimum (mg/L)	0.0	0.0	2.5	3.7	2.6	4.7
Number not detected (#ND)	1	1	0	0	0	0
Percent not detected (%ND)	0	1	0	0	0	0
Number > 20 mg/L HA (#)	55	24	30	1	0	0
Percent > 20 mg/L HA (%)	25	22	33	11	0	0

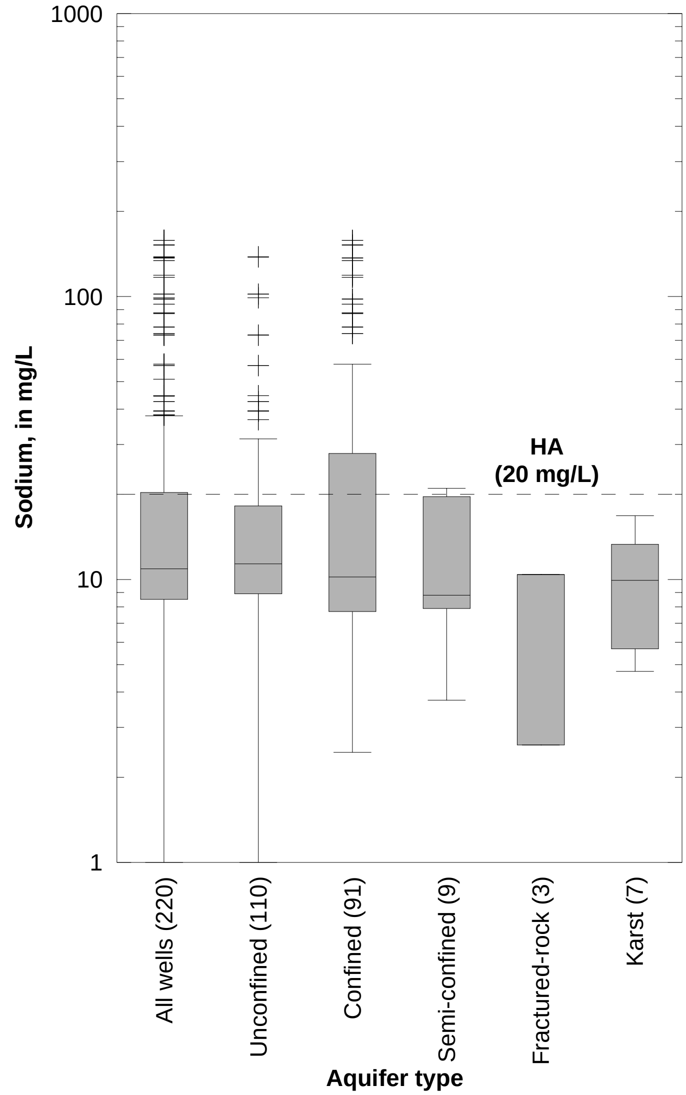

Figure 11. Percentile diagrams of sodium data by aquifer type. [mg/L, milligrams per liter; crosses, outliers; (#), number of samples; HA, health advisory for public water-supply systems (U.S. EPA, 2009); nondetects assigned values of 1 mg/L to allow display on semi-logarithmic plot.]

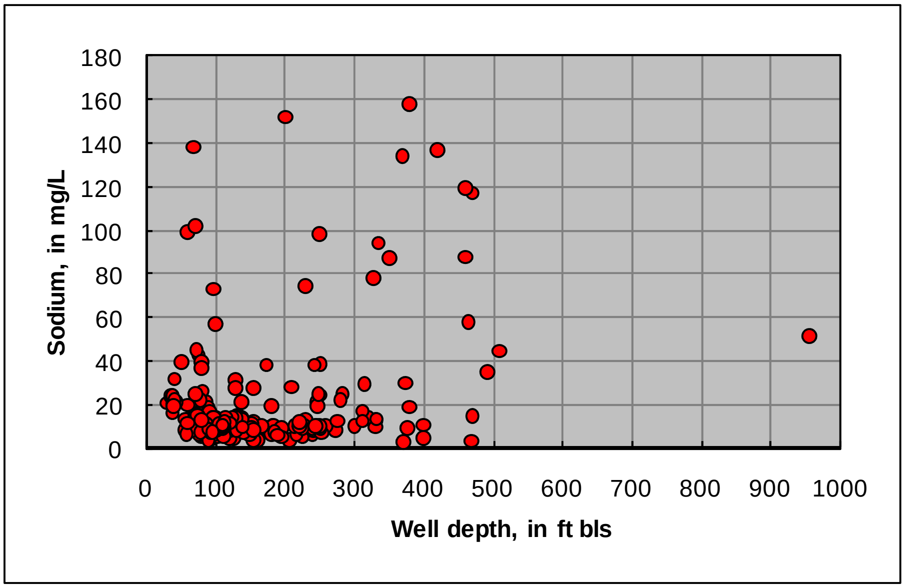

Figure 12. Scatter plot of sodium versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface.]

Iron

Overall, 990 iron analyses are in the SDWIS query provided to DNREC. Of these, 417 (42%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 221 iron analyses where aquifer type is known (Table 6). This number translates to ~23% of the total number of wells (942) where aquifer type is known (Figure 2). Overall, iron concentrations ranged from nondetectable to 33.4 mg/L with a median value of 0.07 mg/L (Table 6 and Figure 13). Iron was not detected above the laboratory quantitation limit in 89 (40%) of the 221 analyses. Iron concentrations exceeded the SMCL (0.3 mg/L) in 66 (30%) of the 221 samples (Table 6).

Confined and semi-confined wells had the highest median iron concentrations (0.19 and 0.16 mg/L, respectively) and the largest fractions of concentrations above the SMCL (40 and 44%, respectively; Table 6 and Figure 13). (Although fractured-rock wells had the highest median iron concentration (0.27 mg/L), the value was not considered accurate do to very limited data.) Unconfined wells had the lowest median iron concentration (nondetectable) and the largest fraction nondetectable concentrations (55%). The most elevated iron concentration (33.4 mg/L), however, was associated with an unconfined well. Iron concentrations exceeded the SMCL in 22% of the unconfined-well samples, a fraction that compares well with Ferrari (2001; 17%). Karst wells had the second-lowest median iron concentration (0.010 mg/L) and a very narrow range in concentration (Table 6 and Figure 13). Furthermore, iron concentrations in karst well samples never exceeded the SMCL. Overall, iron exceeded the SMCL at virtually all depths (Figure 14).

Table 6. Statistical summary of iron data by aquifer type. [mg/L, milligrams per liter; ND, not detected; SMCL, secondary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2009).]

STATISTICS	ALL WELLS	UNCONFINED WELLS	CONFINED WELLS	SEMI-CONFINED WELLS	FRACTURED-ROCK WELLS	KARST WELLS
Number of wells/samples (#)	221	110	92	9	3	7
Percent of total (%)	100	50	42	4	1	3
Maximum (mg/L)	33.40	33.40	22.60	11.45	0.35	0.010
75th percentile (mg/L)	0.56	0.16	1.62	0.44	0.31	0.010
50th percentile (mg/L)	0.07	0.00	0.19	0.16	0.27	0.010
25th percentile (mg/L)	0.00	0.00	0.00	0.00	0.22	0.005
Minimum (mg/L)	0.00	0.00	0.00	0.00	0.17	0.005
Number not detected (#ND)	89	60	25	4	0	0
Percent not detected (%ND)	40	55	27	44	0	0
Number > 0.3 mg/L SMCL (#)	66	24	37	4	1	0
Percent > 0.3 mg/L SMCL (%)	30	22	40	44	33	0

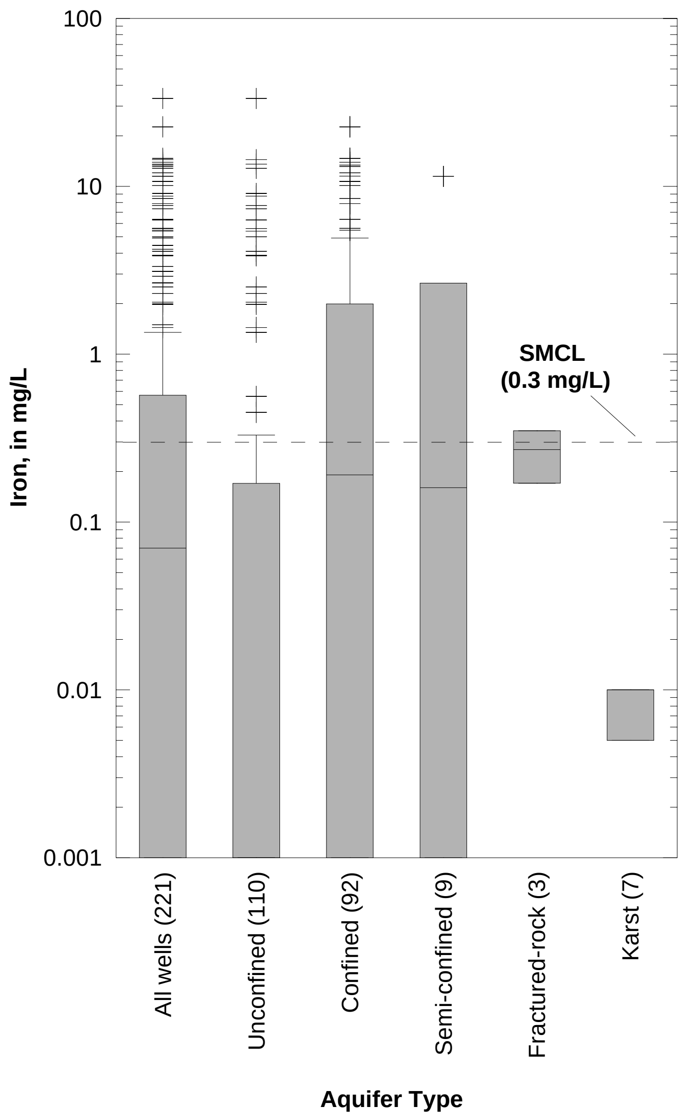

Figure 13. Percentile diagrams of iron data by aquifer type. [mg/L, milligrams per liter; crosses, outliers; (#), number of samples; SMCL, secondary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2009); nondetects assigned values of 0.001 mg/L to allow display on semi-logarithmic plot.]

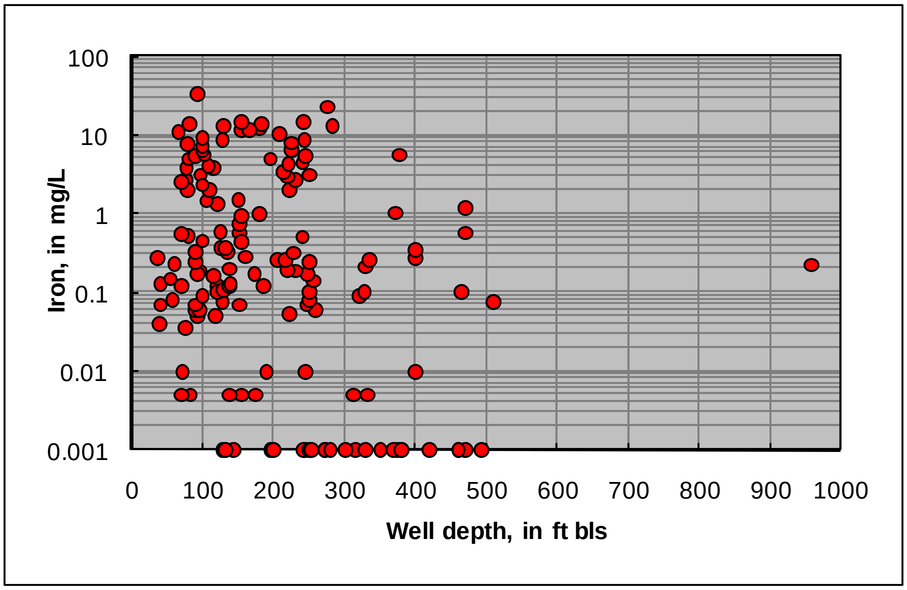

Figure 14. Scatter plot of iron versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface; nondetects assigned values of 0.001 mg/L to allow display on semi-logarithmic plot.]

Hardness as $CaCO_3$

Overall, 735 hardness as $CaCO_3$ ("hardness") analyses are in the SDWIS query provided to DNREC. Of these, 369 (50%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 216 hardness analyses where aquifer type is known (Table 7). This number translates to ~23% of the total number of wells (942) where aquifer type is known (Figure 2). Overall, hardness concentrations ranged from nondetectable to 371 mg/L with a median value of 19.8 mg/L (Table 7 and Figure 15). Hardness was not detected above the laboratory quantitation limit in 33 (15%) of the 216 analyses. With respect to the hardness scale of Love (1962), most of the analyses (199 or 92%) were classified as soft or moderately hard (Table 7). The remaining 8% of the analyses were classified as either hard (6%) or very hard (2%).

Karst wells had the highest median hardness concentration (320 mg/L) and the largest (and only) fraction of concentrations (71%) classified as very hard (Table 7 and Figure 15). The hardness results for karst wells are in general agreement with Werkheiser (1995), who reported that more than 75% of karst well samples could be classified as very hard. Hardness data for karst and fractured-rock wells are in sharp contrast (Table 7 and Figure 15), consistent with Werkeiser (1995); however, there are limited data for fractured-rock wells in this assessment. Confined wells had the second-highest median hardness concentration (52.7 mg/L) and the second-largest fraction of samples classified as moderately hard or harder (42%; Table 7). Hardness data for unconfined and semi-confined wells were generally comparable in terms of median hardness concentrations (10.9 and 15.7 mg/L, respectively) and the fractions of results classified as soft (94 and 89%, respectively). Overall, there is no apparent trend in hardness with depth (Figure 16). At depths shallower than 100 ft bls, however, groundwater was almost always classified as either soft or moderately hard.

Table 7. Statistical summary of hardness data by aquifer type. [mg/L, milligrams per liter; ND, not detected; hardness scale after Love (1962).]

STATISTICS	ALL WELLS	UNCONFINED WELLS	CONFINED WELLS	SEMI-CONFINED WELLS	FRACTURED-ROCK WELLS	KARST WELLS
Number of wells/samples (#)	216	108	89	9	3	7
Percent of total (%)	100	50	41	4	1	3
Maximum (mg/L)	371.0	108.0	172.0	122.0	31.8	371.0
75th percentile (mg/L)	56.6	19.8	77.5	45.0	27.3	338.5
50th percentile (mg/L)	19.8	10.9	52.7	15.7	22.8	320.0
25th percentile (mg/L)	8.8	6.0	26.0	0.0	19.0	221.0
Minimum (mg/L)	0.0	0.0	0.0	0.0	15.1	176.0
Number not detected (#ND)	33	25	5	3	0	0
Percent not detected (%ND)	15	23	6	33	0	0
Soft; 0-60 mg/L (#)	165	102	52	8	3	0
Soft; 0-60 mg/L (%)	76	94	58	89	100	0
Mod. hard; 61-120 mg/L (#)	34	6	28	0	0	0
Mod. hard; 61-120 mg/L (%)	16	6	31	0	0	0
Hard; 121-180 mg/L (#)	12	0	9	1	0	2
Hard; 121-180 mg/L (%)	6	0	10	11	0	29
Very hard; >180 mg/L (#)	5	0	0	0	0	5
Very hard; >180 mg/L (%)	2	0	0	0	0	71

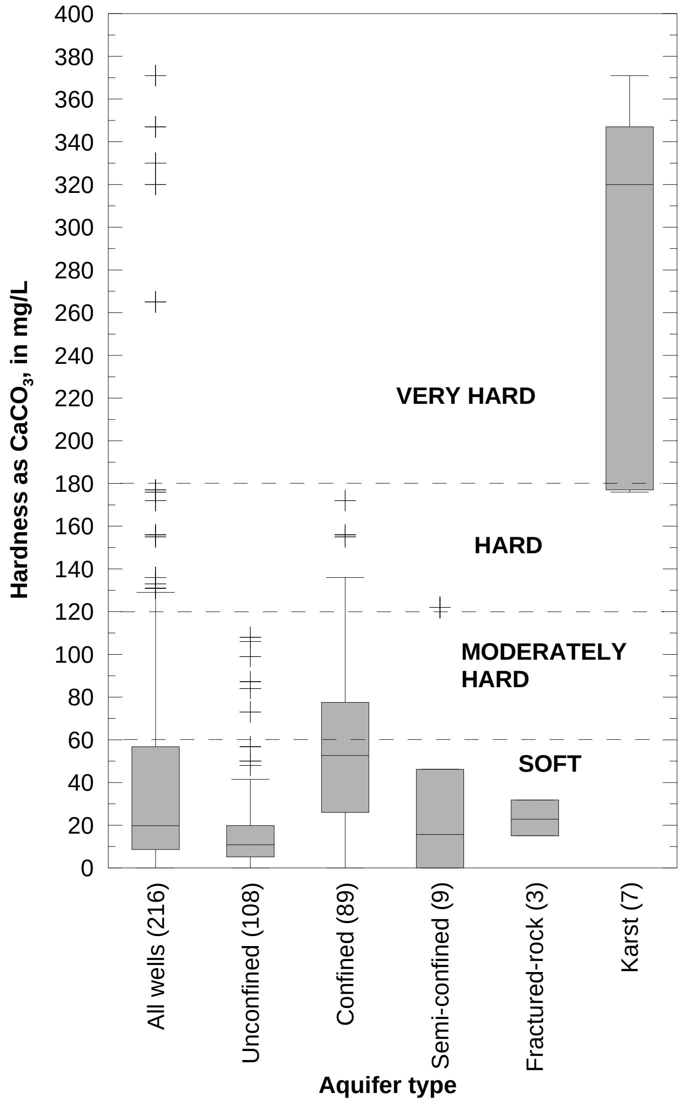

Figure 15. Percentile diagrams of hardness data by aquifer type. [mg/L, milligrams per liter; crosses, outliers; (#), number of samples; hardness scale after Love (1962).]

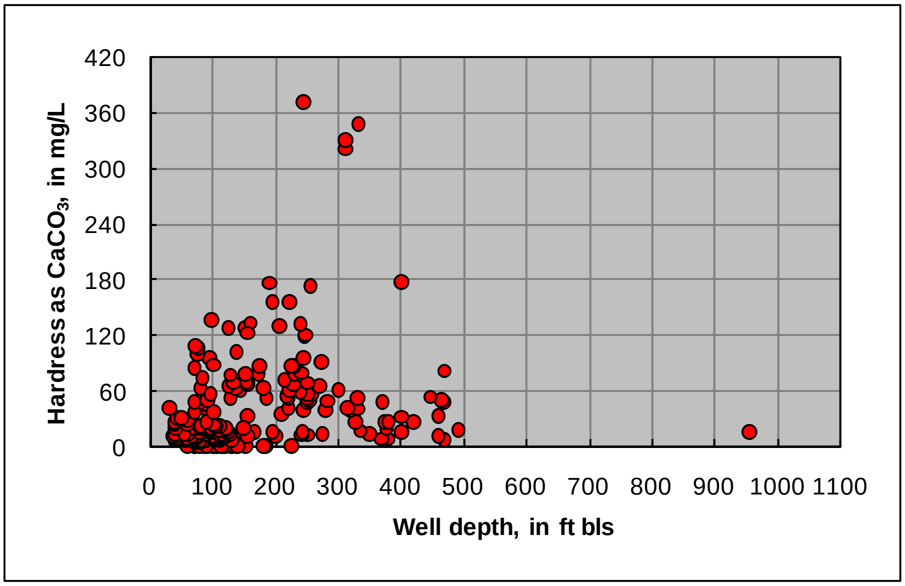

Figure 16. Scatter plot of hardness versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface.]

pH

Overall, 952 pH analyses are in the SDWIS query provided to DNREC. Of these, 343 (36%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 190 pH analyses where aquifer type is known (Table 8). This number translates to ~20% of the total number of wells (42) where aquifer type is known (Figure 2). Overall, pH ranged from 4.0 to 8.6 standard units (S.U.) with a median value of 6.1 S.U. (Table 8 and Figure 17). Values of pH were below the lower limit of the SMCL range (6.5 to 8.5 S.U.) in 113 (~60%) of the 118 samples (Table 8). Only one pH value exceeded the upper limit of the SMCL range.

Karst and confined wells had the highest median pH values (7.8 and 7.6 S.U., respectively) and the largest fractions of samples within the SMCL range (100 and 73.3%, respectively; Table 8). Semi-confined wells had a relatively lower median pH value (6.5 S.U.), but the fraction of samples within the SMCL range (71.4%) was comparable to confined wells. Calcium carbonate in the karst aquifer (due to marble) and some confined and semi-confined aquifers (due to shell material) buffers the pH of the groundwater that recharges and flows through these aquifers. Unconfined wells had the lowest median pH value (5.6 S.U., respectively) and the largest fraction of values below 6.5 S.U. and outside the SMCL range (94%%, respectively; Table 8 and Figure 17). With only three results, pH data for fractured-rock wells are limited. Overall, pH values below 6.5 S.U. occurred at nearly all depths, but were most prevalent at depths of ~150 ft bls or shallower (Figure 18).

Table 8. Statistical summary of pH data by aquifer type. [S.U., standard units; SMCL, secondary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2009).]

STATISTICS	ALL WELLS	UNCONFINED WELLS	CONFINED WELLS	SEMI-CONFINED WELLS	FRACTURED-ROCK WELLS	KARST WELLS
Number of wells/samples (#)	190	98	75	7	3	7
Percent of total (%)	100.0	51.6	39.5	3.7	1.6	3.7
Maximum (S.U.)	8.6	8.3	8.6	7.9	8.1	8.1
75th percentile (S.U.)	7.6	5.9	8.0	6.5	7.6	7.8
50th percentile (S.U.)	6.1	5.6	7.6	6.5	7.1	7.8
25th percentile (S.U.)	5.6	5.3	6.5	6.2	6.7	7.8
Minimum (S.U.)	4.0	4.0	5.6	5.6	6.3	7.4
pH <6.5 SMCL (#)	113	92	18	2	1	0
pH <6.5 SMCL (%)	59.5	93.9	24.0	28.6	33.3	0.0
pH 6.5 to 8.5 (#)	75	6	55	5	2	7
pH 6.5 to 8.5 (%)	39.5	6.1	73.3	71.4	66.7	100.0
pH >8.5 SMCL (#)	1	0	1	0	0	0
pH >8.5 SMCL (%)	0.5	0.0	1.3	0.0	0.0	0.0

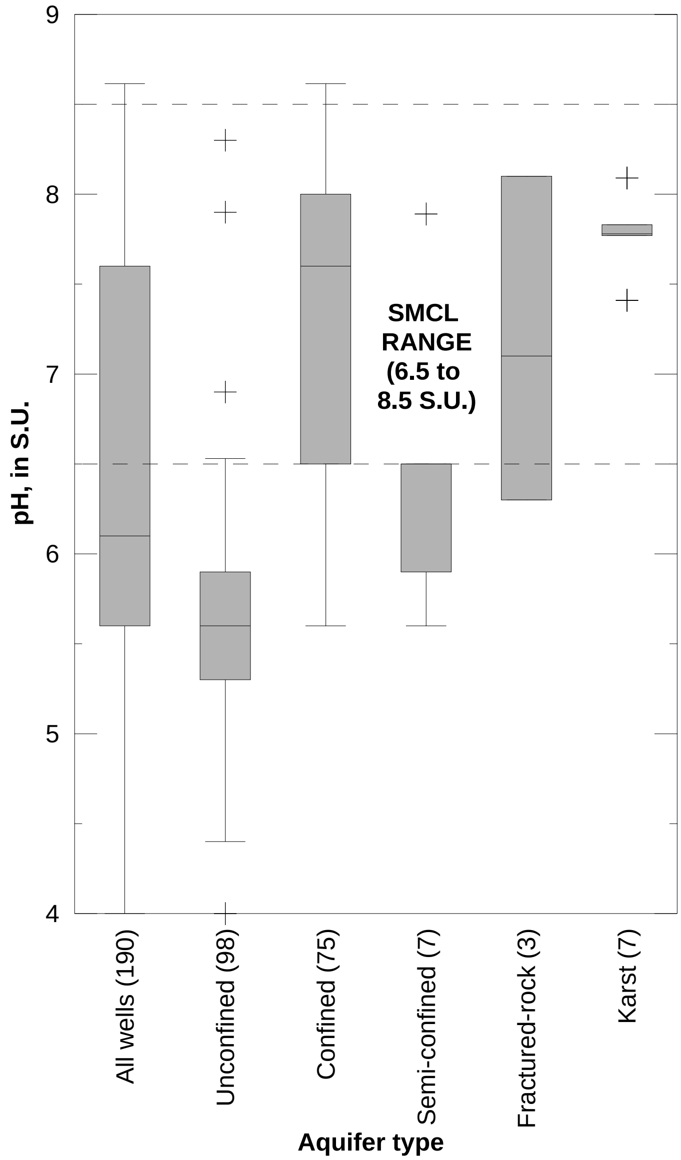

Figure 17. Percentile diagrams of pH data by aquifer type. [S.U., standard units; crosses, outliers; (#), number of samples; SMCL, secondary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2009).]

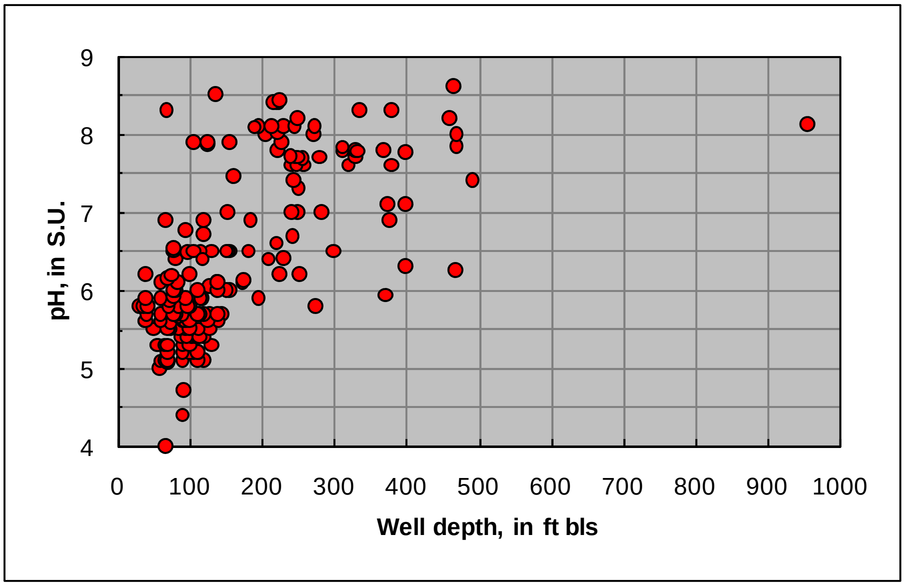

Figure 18. Scatter plot of pH versus well depth. [S.U., standard units; ft bls, feet below land surface.]

Organic compounds

Because organic compounds (OCs) include a broad list of volatiles, semi-volatiles, and pesticides, they are treated in this report as a group of analytes rather than individual analytes. Overall, 37,169 OC analyses are in the SDWIS query provided to DNREC. Duplicate analyses for individual wells were averaged resulting in 8,322 OC analyses. OCs were not detected in 8,156 (98%) of the 8,322 analyses. Out of the 61 organic compounds analyzed, 34 (56%) were detected (Figure 19).

Of the 166 OC detections, about half (82 or 49.4%) were found at concentrations less than 1 µg/L. Chloroform, a disinfection byproduct, was the most-frequently detected OC, consistent with Ferrari's (2001) study of 30 unconfined public water-supply wells in Delaware and DNREC's 2008 305(b) groundwater-quality assessment (Kasper, 2008; Figure 19). Di (2-ethylhexyl)-phthalate (DEHP), a plasticizer and common laboratory contaminant, was the second-most frequently detected OC. Methyl tert-butyl ether (MTBE), a gasoline additive, was the third most-frequently detected OC (Figure 19), consistent with Ferrari (2001) and Kasper (2008).

PMCLs were exceeded in 13 (0.2%) of the 8,322 analyses. The following six analytes were found above the PMCL: tetrachloroethylene (PCE; 5 exceedences), trichloroethylene (TCE; 2 exceedences), methyl tert-butyl ether (MTBE; 2 exceedences), di(2-ethylhexyl)-phthalate (2 exceedences), chloroform (1 exceedence), and dichloromethane (1 exceedence). Aquifer type was established for 9 of the 13 samples with PMCL exceedences. Of these, four were associated with confined wells, three were associated with unconfined wells, and two were associated with karst wells. All of the confined wells are completed in the Potomac aquifer system, an extremely heterogeneous fluvial system used most extensively for water supply in the northern, most populated portion of the State (McKenna et al., 2004). This finding, albeit limited, further illustrates the susceptibility of the unconfined aquifer, karst aquifer, and Potomac aquifer system to contamination.

MTBE, TCE, and PCE are within the top ten most frequently detected OCs (Figure 19), consistent with Ferrari's (2001) findings and DNREC's 2008 305(b) groundwater-quality assessment (Kasper, 2008). Well depths were established for 73 MTBE, 75 TCE, and 75 PCE analyses, and scatter plots of these parameters versus well depth are shown in Figure 20. MTBE was never detected below depths of 200 ft bls, consistent with Kasper (2008). TCE and PCE, however, were detected at greater depths, the deepest of which was a PCE detection in a 312-ft deep well. All of the TCE and PCE detections at depths greater than 200 ft bls were associated with karst wells. These results cannot be compared with Kasper (2008) as water-quality data for karst wells were not represented in that assessment. Overall, these findings are consistent with trends of nitrate versus well depth (Figure 5), and appear to provide another indication of the vertical extent of human impact on groundwater quality in Delaware.

Due to the frequency of MTBE detections (Figure 19) and its mobility in groundwater, the spatial variability of this contaminant was evaluated for unconfined and confined public wells (Figures 21a and 21b). These aquifer types were selected for further analysis because they are the most-extensively used aquifers in Delaware (Figure 2) and the most well represented in the dataset. For unconfined wells, 18 MTBE analyses were linked by DNREC ID. Of these, MTBE was detected in 7 (39%) of the analyses. Two of the detections were associated with unconfined wells in northern New Castle County and the remaining five detections were associated with unconfined wells in Sussex County (Figure 21a). No MTBE data were linked by DNREC ID for unconfined wells in Kent County. For confined wells, 30 MTBE analyses were linked by DNREC ID. Of these, MTBE was detected in 4 (~13%) of the analyses, and all of the detections were associated with Potomac aquifer wells located in northern New Castle County (Figure 21b).

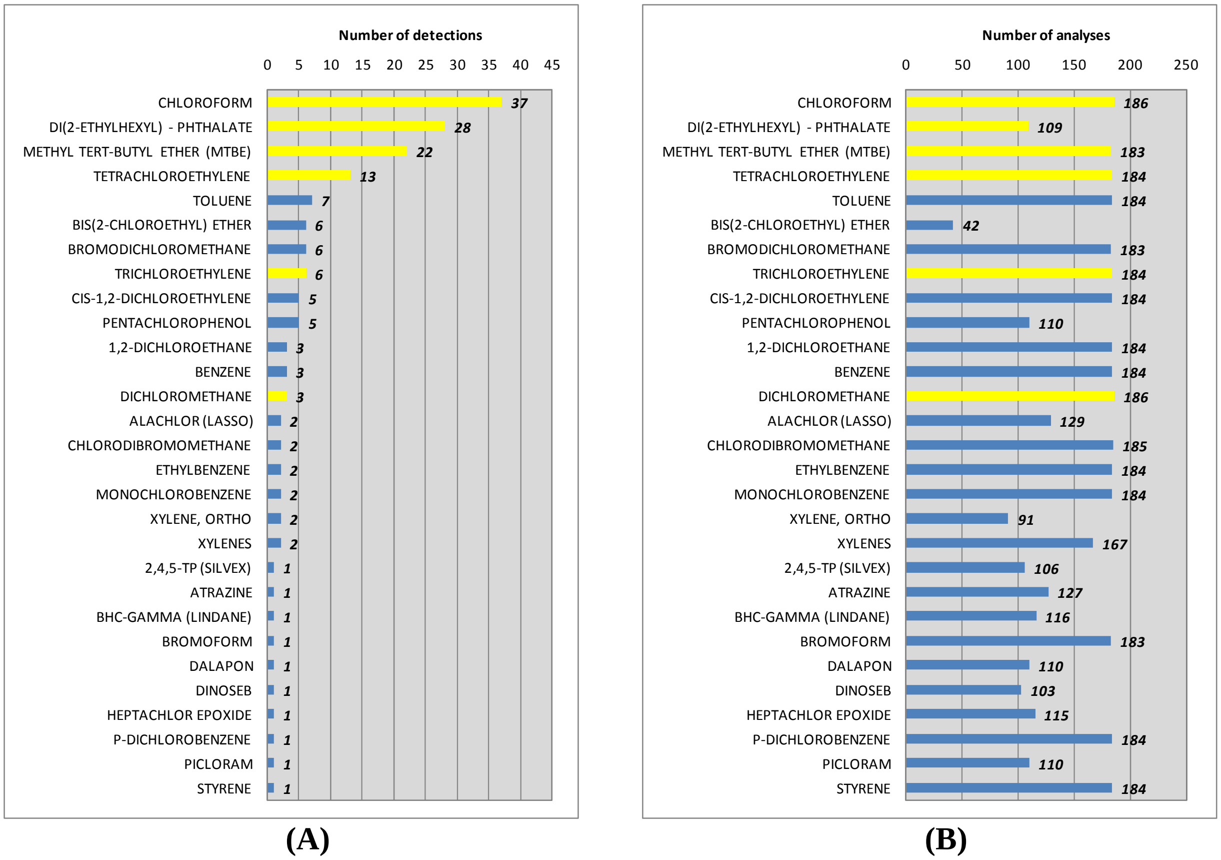

Figure 19. Frequency distributions of organic compound (A) detections and (B) analyses. [Bars highlighted yellow indicate one or more concentration above the PMCL.]

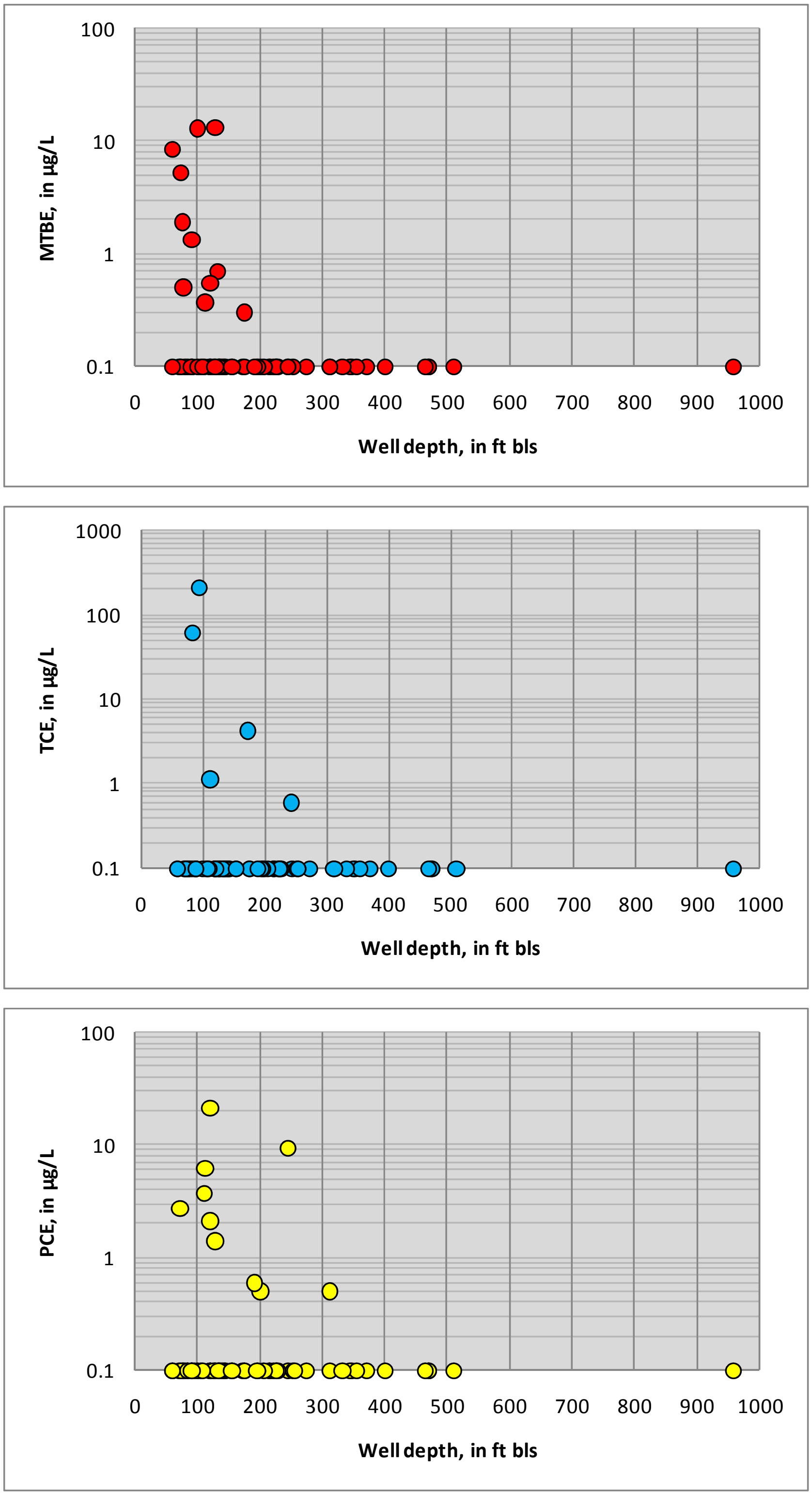

Figure 20. Scatter plots of methyl tert-butyl ether (MTBE), trichloroethylene (TCE), and tetrachloroethylene (PCE) versus well depth. [µg/L, micrograms per liter; ft bls, feet below land surface; PMCLs (DHSS, 2005; U.S. EPA, 2009): MTBE (10 µg/L), TCE (5 µg/L), and PCE (5 µg/L); nondetectable concentrations (zeros) assigned values of 0.1 µg/L to allow display on semi-logarithmic plots.]

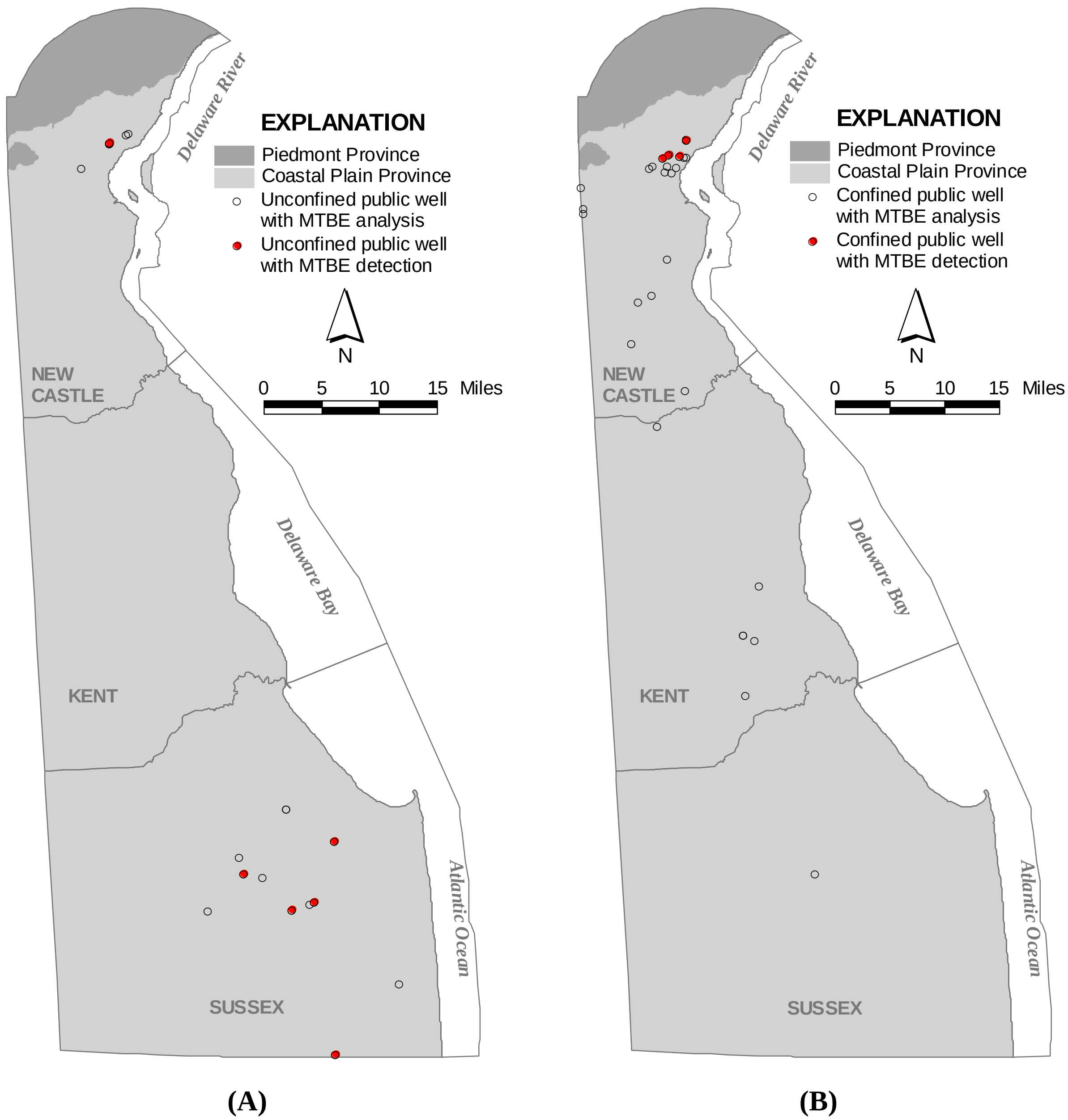

Figure 21. Maps showing methyl tert-butyl ether (MTBE) analyses and detections in (A) unconfined and (B) confined public water-supply wells.

Trace elements

For this assessment, trace elements are limited to the following analytes with PMCLs (DHSS, 2005; U.S. EPA, 2009): antimony (0.006 mg/L), arsenic (0.01 mg/L), barium (2 mg/L), beryllium (0.004 mg/L), cadmium (0.005 mg/L), chromium (0.1 mg/L), cyanide (0.2 mg/L), fluoride (2 mg/L), lead (0.015 mg/L*), mercury (0.002 mg/L), nickel (0.1 mg/L), selenium (0.05 mg/L), and thallium (0.002 mg/L). (*Action level for Treatment Technique (TT; U.S. EPA, 2009).) Overall, 3,560 trace-element analyses are in the SDWIS query provided to DNREC.

Duplicate analyses for individual wells were averaged resulting in 1,999 trace-element analyses. Trace elements were not detected in 1,485 (74%) of the 1,999 analyses.

Detectable trace-element concentrations were less than 0.1 mg/L in 349 (68%) of the 514 detections and less than 1 mg/L in 509 (99%) of the 514 detections. Barium, nickel, and chromium were the three most-frequently detected trace elements (Figure 22). (Although fluoride had the largest number of detections (171), it also had the largest number of analyses (578) and it was detected in a relatively small percentage (30%) of those analyses (Figure 22).) Barium was detected in 87 (74%) of the 118 analyses, nickel was detected in 70 (61%) of 115 analyses, and chromium was detected in 69 (59%) of 117 analyses (Figure 22). PMCLs or action levels were exceeded in 4 (0.2%) of the 1,999 analyses. The following two analytes were found above the PMCL: arsenic (3 exceedences) and nickel (1 exceedence). Aquifer type was established for 2 of the 3 wells with arsenic concentrations above the PMCL; these wells produce from the Piney Point and Rancocas aquifers, both of which contain the mineral glauconite. This finding is consistent with Drummond and Bolton (2010). The single well with nickel above the PMCL is a confined well completed in the Potomac aquifer system in northern New Castle County.

The fate, transport, and remediation of arsenic in Delaware soil are topics of recent investigation (DNREC, 2005; Sparks et al., 2007). Published data on arsenic in Delaware's groundwater are generally lacking, however, and limited to the surficial aquifer system (see, for e.g., Denver et al., 2004). Sources of arsenic in groundwater on the Delmarva Peninsula include, but are not limited to, poultry manure applied to agricultural fields, pesticides and fertilizers, abandoned tanneries, lumber treated with chromium copper arsenate, and glauconitic sediments deposited in marine environments (Denver et al., 2004; DNREC, 2005). A recent study of arsenic in groundwater in the Coastal-Plain aquifers of Maryland (Drummond and Bolton, 2010) found that arsenic concentrations in excess of the PMCL were primarily limited to the Piney Point and Aquia aquifers. (Note that the Aquia aquifer of Maryland is analogous to the Rancocas aquifer of Delaware.) Arsenic in these aquifers is apparently due to naturally-occurring sources, which may include calcareous shell material and cement, glauconite grains, phosphate pellets, goethite pellets, and iron oxyhydroxide coatings on mineral grains (Drummond and Bolton, 2010).

In this assessment, arsenic was detected in 18 (14%) of 130 analyses (Figure 22). Detections ranged from 0.0005 to 0.0336 mg/L. As previously noted, arsenic exceeded the PMCL (0.01 mg/L) in three wells or ~2% of the 130 analyses. Aquifer type was established for 59 (45%) of the 130 analyses. Of these 59 analyses, 20 were associated with unconfined wells, 1 was associated with a semi-confined well, 31 were associated with confined wells, and 7 were associated with karst wells. Arsenic was not detected in the semi-confined well or the karst wells.

Arsenic was detected in 1 of the 20 unconfined well samples; however, the data are lacking both spatially and in number (Figure 23a). Moreover, arsenic data could not be mapped for unconfined wells in the north-central portion of Delaware (Figure 1b) where glauconitic formations outcrop or subcrop surficial formations (Ramsey, 2005, 2007) and, in places, function as part of the unconfined aquifer. The single unconfined arsenic detection was associated with a well located in Sussex County and screened in the Cat Hill Formation (Figure 23a). The Cat Hill Formation is a predominantly sandy marine deposit with glauconite as a rare accessory component (Andres, 2004). Arsenic analyses for confined wells are limited to wells located in New Castle County and Kent County (Figure 23b). Arsenic was detected in 4 of the 31 confined well samples. Three of these wells are located near the boundary separating New Castle County and Kent County; the remaining well is located in southern Kent County (Figure 23b). These wells produce from the Rancocas, Mt. Laurel, and Piney Point aquifers, all of which are associated with glauconitic geologic formations (Ramsey, 2005, 2007). As previously noted, the two confined wells with arsenic above the PMCL produce from the Piney Point and Rancocas aquifers.

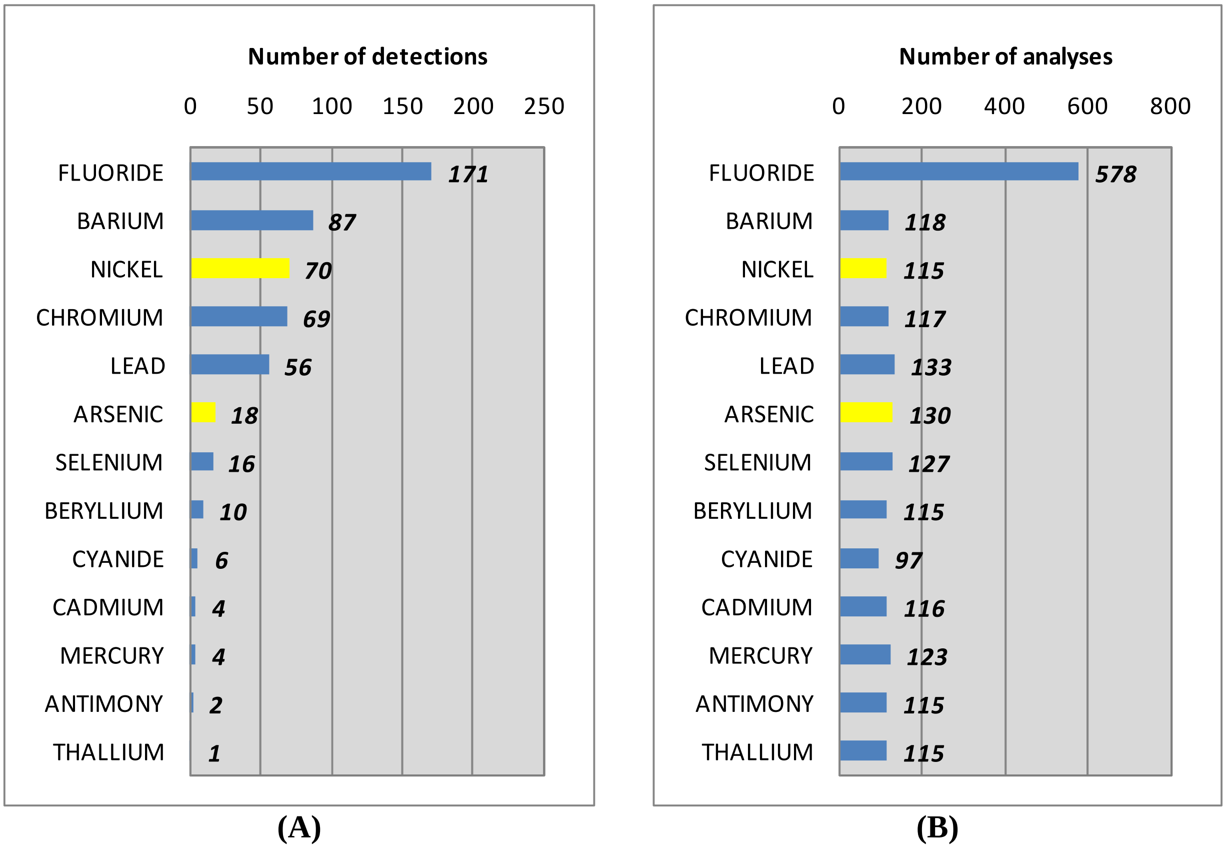

Figure 22. Frequency distributions of trace element (A) detections and (B) analyses. [Bars highlighted yellow indicate one or more concentration above the PMCL.]

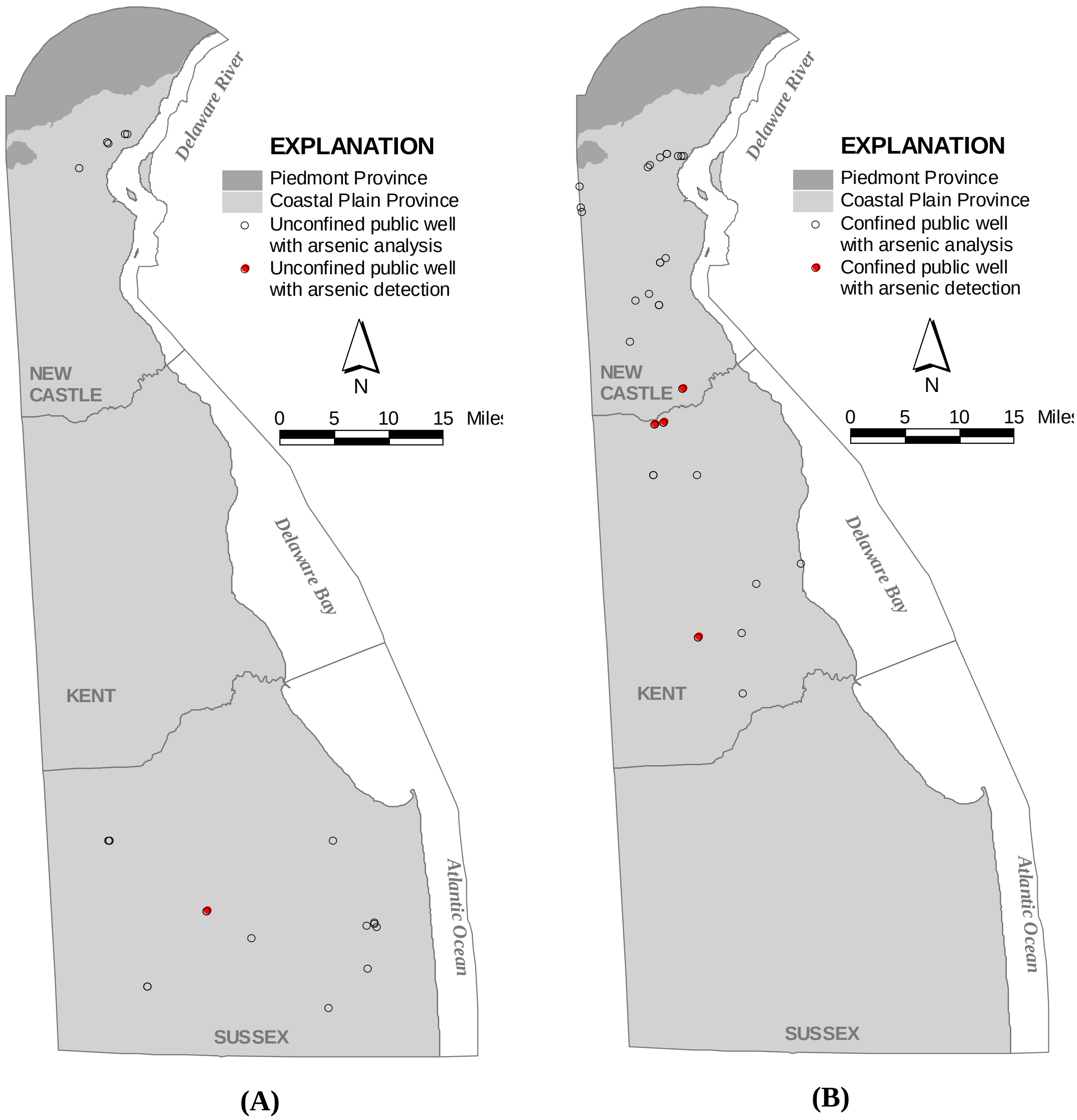

Figure 23. Maps showing arsenic analyses and detections in (A) unconfined and (B) confined public water-supply wells.

Radionuclides

Radionuclide data are limited to the following parameters: uranium-238, radium-226 and radium-228 combined, and gross alpha particle activity. The PMCLs for these parameters are 0.03 mg/L, 5 pCi/L, and 15 pCi/L (DHSS, 2005; U.S. EPA, 2009). Overall, 416 radionuclide analyses are in the SDWIS query provided to DNREC; this number reflects the parameters listed above as well as individual analyses for radium-226 and radium-228. Duplicate analyses for individual wells were averaged resulting in 211 radionuclide analyses, summarized as follows: uranium-238 (68 analyses), radium-226 and radium-228 combined (4 analyses), radium-226 (6 analyses), radium-228 (64 analyses), and gross alpha particle activity (69 analyses). None of the concentrations or activities exceeded the respective PMCLs. For more information on radionuclides in Delaware groundwater, the reader is referred to Bachman and Ferrari (1995) and Ferrari (2001). Studies in the Coastal-Plain regions of Maryland (Bolton, 2000) and New Jersey (Szabo and dePaul, 1998; Szabo et al., 2004; dePaul and Szabo, 2007) also have been conducted.

Summary and conclusions

The Department of Natural Resources and Environmental Control (DNREC) assessed groundwater quality in Delaware based on data collected during 2008-09 from public water-supply wells. The results of this assessment serve as "Part IV: Groundwater Assessment" of Delaware's overall 2010 305(b) report (DNREC, 2010). Water-quality data were obtained from the Department of Health and Social Services (DHSS) Safe Drinking Water Information System (SDWIS). SDWIS queries developed by DHSS staff provide data (53,141 analyses) indicative of raw or apparently raw groundwater quality. Water-quality data were linked with the DNREC's Source Water Assessment and Protection Program (SWAPP) database, which contains public-well records such as DNREC ID, depth, geographic coordinates, geologic formation, aquifer, and aquifer type. Per U.S. EPA (1997) guidance, data were evaluated with respect to hydrogeologic setting where possible and drinking-water standards or criteria where applicable (DHSS, 2005; U.S. EPA, 2009; Love, 1962).

Five aquifer types were recognized in this assessment: unconfined, confined, semi-confined, fractured-rock, and karst aquifers. Unconfined, confined, and semi-confined aquifers occur in the mid-Atlantic Coastal Plain Physiographic Province, which comprises most (~96%) of Delaware's land-surface area. Fractured-rock and karst aquifers occur in the Piedmont Physiographic Province in the northernmost portion of the state. As of April 2010, there were 1,121 active public water-supply wells in Delaware. Most of the wells (78%) produce from Coastal-Plain aquifers while a much smaller percentage of the wells (6%) produce from Piedmont aquifers. Aquifer type could not be established for the remaining 16% of the wells. Overall, well depths range from 22 to 957 ft below land surface (bls) with a median well depth of 135 ft bls.

Overall, groundwater is predominantly soft or moderately hard based on the hardness scale of Love (1962). Specifically, most of the results (92%) meet either of these criteria. With respect to aquifer type, fractions of hardness results classified as soft or moderately hard are summarized as follows: unconfined wells (100%), confined wells (89%), semi-confined wells (89%), and fractured-rock wells (100%). In contrast, all of the hardness results for karst wells were classified as hard or very hard. Groundwater also is predominantly acidic overall, with pH values less than the lower limit of the Secondary Maximum Contaminant Level (SMCL) range (6.5 to 8.5 S.U.) in ~60% of the samples. Unconfined wells had the largest fraction of pH values below the SMCL range (94%); in contrast, confined, semi-confined, fractured-rock, and karst wells had pH values that were predominantly within the SMCL range. Overall, iron exceeded the 0.3 mg/L SMCL in a considerable fraction of the samples (30%) and was found above the SMCL in all aquifer types and at virtually all depths. Semi-confined and confined aquifers, however, had the largest fractions of concentrations greater than the SMCL (44 and 40%, respectively). Total dissolved solids (TDS) concentrations never exceeded the 500 mg/L SMCL, although this level was approached in a confined well sample (472 mg/L). Karst wells had the highest median TDS concentration (416 mg/L). Chloride concentrations never exceeded the SMCL (250 mg/L), although this value was approached in an unconfined well sample (222 mg/L). Karst wells had the highest median chloride concentration (39.4 mg/L), consistent with the TDS data. Sodium concentrations exceeded the 20 mg/L Health Advisory or HA in a considerable fraction of the samples (25%) and at virtually all depths. Confined wells had the largest fraction of concentrations above the HA (33%).

Nitrate was used as a proxy to indicate the extent of human influence on groundwater quality. Overall, most of the wells (54%) had nitrate concentrations greater than 0.4 mg/L, a threshold indicative of anthropogenic impacts (Hamilton et al., 1993). Of the aquifer types evaluated, the unconfined and karst aquifers appear to be the most susceptible to human impacts. These aquifers had the highest median nitrate concentrations (3.79 and 3.22 mg/L, respectively) and the largest fractions of concentrations greater than 0.4 mg/L (82 and 100%, respectively). The unconfined aquifer also had the most elevated nitrate concentration (24 mg/L) and the second-largest fraction of concentrations above the 10 mg/L Primary Maximum Contaminant Level or PMCL (11%). Nitrate concentrations in the karst aquifer never exceeded the PMCL, however. The fractured-rock and semi-confined aquifers had intermediate median nitrate concentrations (2.60 and 1.45 mg/L, respectively) and equal fractions of concentrations greater than 0.4 mg/L (67%). The fractured-rock aquifer, however, is not well represented in this assessment due to limited data. Semi-confined aquifers also had the second-highest nitrate concentration (23 mg/L) and the largest fraction of concentrations above the PMCL (17%). Confined aquifers, in sharp contrast, had the lowest median nitrate concentration (zero mg/L or nondetectable) and the smallest fraction of concentrations greater than 0.4 mg/L (15%). Confined aquifers also had the largest fraction of nondetectable nitrate concentrations (84%). Nitrate exceeded the PMCL in 1 (1%) of the confined well analyses, however, suggesting either poor confinement or compromised well construction. Regardless of aquifer type, the vertical extent of human influence was limited to depths 400 ft below land surface (bls) and shallower, with the deepest detections above 0.4 mg/L associated with wells in the fractured-rock and karst aquifers. At greater depths nitrate was rarely detected above the quantitation limit. Areally, PMCL exceedences were limited to the southern portion of Delaware.

Organic compounds (OCs) were not frequently detected and, when detected, rarely exceeded PMCLs. Specifically, OCs were not detected in 98% of 8,322 analyses. Of the 166 OC detections, about half (82 or 49.4%) were found at concentrations less than 1 µg/L. Chloroform, a disinfection byproduct, was the most-frequently detected OC, consistent with Ferrari (2001) and Kasper (2008). PMCLs were exceeded in a very small fraction (13 or 0.2%) of the analyses, summarized as follows: tetrachloroethylene (PCE; 5 exceedences), trichloroethylene (TCE; 2 exceedences), methyl tert-butyl ether (MTBE; 2 exceedences), di(2-ethylhexyl)-phthalate (2 exceedences), chloroform (1 exceedence), and dichloromethane (1 exceedence). PMCL exceedences that could be linked by aquifer type were associated with confined wells in the Potomac aquifer system, unconfined wells, and karst wells. Methyl tert-butyl ether (MTBE), trichloroethylene (TCE), and tetrachloroethylene (PCE) were among the top-ten most-frequently detected OCs, consistent with Ferrari (2001) and Kasper (2008), and each had results above their respective PMCLs. Concentrations of MTBE, TCE, and PCE with respect to sample depth indicate that the vertical extent of human impact is limited to depths of ~300 ft bls and shallower, with the deepest concentrations associated with karst wells; at greater depths these contaminants were not detected. As previously noted, similar trends in nitrate with respect to sample depth were identified.

Similar to OCs, trace elements were not frequently detected and rarely exceeded PMCLs when detected. Specifically, trace elements were not detected in 74% of 1,999 analyses. Of the 514 trace-element detections, 349 (68%) were found at concentrations less than 0.1 mg/L and 509 (99%) were found at concentrations less than 1 mg/L. Barium, nickel, and chromium were the top three most-frequently detected trace elements, consistent with Kasper (2008). PMCLs or action levels were exceeded in a very small fraction (4 or 0.2%) of the analyses, summarized as follows: arsenic (3 exceedences) and nickel (1 exceedence). An analysis of arsenic data suggests that that this element is primarily limited to confined wells that produce from the Piney Point and Rancocas aquifers, consistent with Drummond and Bolton (2010).

Radionuclide data were limited to the following parameters: uranium-238, radium-226 and radium-228 combined, and gross alpha particle activity. The PMCLs for these parameters were never exceeded.

This 305(b) groundwater-quality assessment is DNREC's second attempt to report raw or apparently raw groundwater data with respect to hydrogeologic setting on a statewide basis. The results represent a subset of the total number of active public water-supply wells in Delaware and, therefore, should be viewed in that context. Provided that water-quality data in SDWIS continue to be identified by DNREC ID, future 305(b) groundwater-quality assessments should provide a more complete picture of groundwater quality in Delaware.

References

Andres, A.S., 2004, The Cat Hill Formation and Bethany Formation of Delaware: Delaware Geological Survey Report of Investigations No. 67, 8 p.

Bachman, L.J., and Ferrari, M.J., 1995, Quality and geochemistry of groundwater in southern New Castle County, Delaware: Delaware Geological Survey Report of Investigations No. 52, 31 p.

Bolton, D.W., 2000, Occurrence and distribution of radium, gross alpha-particle activity, and gross beta-particle activity in groundwater in the Magothy Formation and Potomac Group aquifers, upper Chesapeake Bay area, Maryland: Maryland Geological Survey Report of Investigations No. 70, 97 p.

Denver, J.M., 1989, Effects of agricultural practices and septic-system effluent on the quality of water in the unconfined aquifer in parts of eastern Sussex County, Delaware: Delaware Geological Survey Report of Investigations No. 45, 66 p.

Denver, J.M., Ator, S.W., Debrewer, L.M., Ferrari, M.J., Barbaro, J.R., Hancock, T.C., Brayton, M.J., Nardi, M.R., 2004, Water quality in the Delmarva Peninsula, Delaware, Maryland, and Virginia, 1999-2001: U.S. Geological Survey Circular 1228, 30 p.

dePaul, V.T., and Szabo, Z., 2007, Occurrence of radium-224, radium-226, and radium-228 in water from the Vincentown and Wenonah-Mount Laurel aquifers, the Englishtown aquifer system, and the Hornerstown and Red Bank Sands, southwestern and south-central New Jersey: U.S. Geological Survey Scientific Investigations Report 2007-5064, 61 p.

DHSS, 2005, State of Delaware Regulations Governing Public Drinking Water Systems: Delaware Department of Health and Social Services, 155 p.

DNREC, 2002, State of Delaware 2002 watershed assessment report (305(b)): Delaware Department of Natural Resources and Environmental Control, 187 p.

DNREC, 2005, Arsenic risk management proposal draft background document: Delaware Department of Natural Resources and Environmental Control, 36 p.

DNREC, 2007, Policy for correlating well sampling results to DNREC well ID numbers: Delaware Department of Natural Resources and Environmental Control, 3 p.

DNREC, 2010, State of Delaware 2010 combined watershed assessment report (305(b)) and determination for the Clean Water Act Section 303(d) list of waters needing TMDLs: Delaware Department of Natural Resources and Environmental Control, 147 p., 2 appendices.

Drummond, D.D., and Bolton, D.W., 2010, Arsenic in ground water in the Coastal Plain aquifers of Maryland: Maryland Geological Survey Report of Investigations No. 78, 71 p.

Ferrari, M.J., 2001, Occurrence and distribution of selected contaminants in public drinking-water supplies in the surficial aquifer of Delaware: U.S. Geological Survey Open-File Report 01-327, 62 p.

Hamilton, P.A., Denver, J.M., Phillips, P.J., and Shedlock, R.J., 1993, Water-quality assessment of the Delmarva Peninsula, Delaware, Maryland, and Virginia—Effects of agricultural activities on, and distribution of, nitrate and other inorganic constituents in the surficial aquifer: U.S. Geological Survey Open-File Report 93-40, 87 p.

Kasper, J.W., 2008, Delaware's 2008 305(b) Ground-water-quality assessment based on public-well data: Delaware Department of Natural Resources and Environmental Control, 45 p.

Kasper, J.W., and Strohmeier, S.A., 2007, Groundwater-quality survey of the Indian River Bay watershed, Sussex County, Delaware: Results of sampling, 2001-03: Delaware Department of Natural Resources and Environmental Control Document No. 40-08-05/07/03/01, 57 p.

Love, S.K., March 22, 1962, Water quality – hardness of water: U.S. Geological Survey Quality of Water Branch Memorandum No. 62.47, 1 p.

McKenna, T.E., McLaughlin, P.P., and Benson, R.N., 2004, Characterization of the Potomac Aquifer, an extremely heterogeneous fluvial system in the Atlantic Coastal Plain of Delaware: Delaware Geological Survey Open File Report 45.

Pellerito, V., Neimeister, M.P., Wolff, E., and Andres, A.S., 2008, Results of the domestic well water-quality study: Delaware Geological Survey Open File Report No. 48, 50 p.

Plank, M.O., Schenck, W.S., and Srogi, L., 2000, Bedrock geology of the Piedmont of Delaware and adjacent Pennsylvania: Delaware Geological Survey Report of Investigations No. 59, 52 p.

Ramsey, K.W., 2005, Geologic map of New Castle County, Delaware: Delaware Geological Survey Geologic Map Series No. 13, scale 1:100,000.

Ramsey, K.W., 2007, Geologic map of Kent County, Delaware: Delaware Geological Survey Geologic Map Series No. 14, scale 1:100,000.

Schenck, W.S., Plank, M.O., and Srogi, L., 2000, Bedrock geologic map of the Piedmont of Delaware and adjacent Pennsylvania: Delaware Geological Survey Geologic Map Series No. 10, scale 1:36,000.

Sparks, D.L., Sims, J.T., Seiter, J., and Gardner, S., 2007, Fate and transport of arsenic in Delaware soils: Assessing potential impacts on water quality: University of Delaware, College of Agriculture and Natural Resources, Department of Plant and Soil Sciences, 97 p.

Spoljaric, N., 1986, Sodium concentrations in water from the Piney Point Formation, Dover area, Delaware: Delaware Geological Survey Report of Investigations No. 40, 14 p.

Szabo, Z., and dePaul, V., 1998, Radium-226 and radium-228 in shallow groundwater, southern New Jersey: U.S. Geological Survey Fact Sheet FS-062-98, 6 p.

Szabo, Z., dePaul, V.T., Kraemer, T.F., and Parsa, B., 2004, Occurrence of radium-224, radium-226, and radium-228 in water from the unconfined Kirkwood-Cohansey aquifer system, Southern New Jersey: U.S. Geological Survey Scientific Investigations Report 2004-5224, 92 p.

Talley, J.H., ed., 1995, Geology and hydrology of the Cockeysville Formation, northern New Castle County, Delaware: Delaware Geological Survey Bulletin No. 19, 59 p.

U.S. EPA, 1997, Guidelines for preparation of the comprehensive State water quality assessments (305(b) reports) and electronic updates: U.S. Environmental Protection Agency, EPA 841-B-97-002A, variously paged.

U.S. EPA, 2009, 2009 edition of the drinking water standards and health advisories: U.S. Environmental Protection Agency, EPA 822-R-09-011, 12 p.

Werkheiser, W.H., 1995, Geohydrology of the Hockessin area with emphasis on the Cockeysville aquifer, *in* Talley, J.H., ed., Geology and hydrology of the Cockeysville Formation, Northern New Castle County, Delaware: Delaware Geological Survey Bulletin No. 19, p. 26-59.