State of Delaware
DEPARTMENT OF
NATURAL RESOURCES &
ENVIRONMENTAL CONTROL
John A. Hughes, Secretary

Delaware's 2008 305(b) Ground-Water-Quality Assessment Based on Public-Well Data

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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 ground-water quality must be reported "…to the extent practicable." Guidelines to this end have consequently been developed (U.S. EPA, 1997).

Delaware's Department of Natural Resources and Environmental Control (DNREC) has attempted to report ambient ground-water quality in previous 305(b) reports (see, for e.g., DNREC, 2002). Previous attempts were based on raw ("well-tap") ground-water data for public water-supply systems in the Safe Drinking Water Information System (SDWIS) maintained by the Department of Health and Social Service (DHSS). Those attempts were limited, however, as there was no way to readily identify the data by specific aquifer, aquifer type (e.g., unconfined), or precise geographic location.

Recently, inter-Departmental policy has been developed to identify all ground-water samples collected in Delaware by the well permit number or "DNREC ID" (DNREC, 2007). 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 ground-water quality investigation. Efforts by DHSS are underway to identify water-quality data for public wells by DNREC ID in SDWIS. There also are provisions in the DNREC (2007) policy for the identification of domestic-well samples by DNREC ID in the DHSS's Laboratory Information Management System (LIMS).

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) ground-water-quality assessment is based on information stored in SDWIS and the SWAPP database.

Purpose and scope

This report serves as "Part IV: Ground-Water Assessment" of Delaware's overall 2008 305(b) report (DNREC, 2008). The primary purpose of this report is to summarize and report ambient ground-water quality data collected from public water-supply wells in Delaware during calendar years 2006 and 2007. Per U.S. EPA (1997) guidance, data are evaluated with respect to hydrogeologic setting where possible. A secondary objective is to establish a better framework for 305(b) reporting of ground-water data in Delaware. 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) ground-water quality data for public water-supply wells. Anita Beckel of the DHSS's Office of Drinking Water (ODW) also is thanked for her assistance with SDWIS data acquisition. Douglas E. Rambo, P.G. (DNREC) assisted with the acquisition of SWAP data. Michael Townshend (DNREC) provided assistance with database query development. John T. Barndt, P.G. (DNREC) reviewed the report and provided useful comments for its improvement.

General hydrogeology

Delaware contains ~2,010 mi^2 and is comprised of two Physiographic Provinces: the Piedmont and the Atlantic Coastal Plain. The Piedmont occupies ~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 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 SWAP 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 SWAP 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 SWAP 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

Ground-water quality in Delaware was evaluated based on pre-existing information stored in two separate databases: the DHSS's SDWIS and the DNREC's SWAP database. DHSS staff developed queries to extract SDWIS records of raw (or apparently raw) ground-water-quality data collected from public water-supply systems during the reporting period (2006-07). Data resulting from these queries (65,182 analyses) were provided to DNREC in an April 17, 2008 Excel spreadsheet. Records obtained from the SWAP database were current as of April 16, 2008. The records included well details such as DNREC ID, depth, geographic coordinates, geologic formation, aquifer, and aquifer type. Limited quality control of the SWAP data was done to ensure consistent reporting of geologic formations and aquifers.

An Access database was developed to link and extract data from SDWIS and the SWAP database. For wells with more than one analysis of a given analyte, results were averaged. Analytes not detected above laboratory quantitation limits ("non detects") 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, 2006). Hardness data were evaluated with respect to the scale of Love (1962). Because only raw (or apparently raw) ground-water 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 ground-water quality in specific aquifers (Table 1). Data also were evaluated with respected 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.

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 May 15, 2008).

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 16, 2008, there were 1,000 active (and 264 inactive or unassigned) public water-supply wells in the SWAP database. Of the active wells, 992 (99%) have geographic coordinates and are plotted in Figure 1A. With reference to Figure 1A, there are 239 wells (24%) in New Castle County, 260 wells (26%) in Kent County, and 493 wells (49%) in Sussex County. (Percentages may not total 100% due to rounding.)

Aquifer type is known for 929 (93%) of the 1,000 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 862 (86%) and Piedmont wells account for 67 (7%) (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 71 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 862 Coastal-Plain wells, unconfined wells account for 392 (45%), confined wells account for 425 (49%), and semi-confined wells account for 45 (5%) (Figure 2). A large majority of the unconfined wells with geographic coordinates (310 of 392 or 79%) are located in Sussex County; the remaining unconfined wells include 44 (4.4%) in Kent County and 37 (3.7%) 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 422 confined wells with geographic coordinates, 171 (41%) are located in Kent County, 127 (30%) are located in New Castle County, and 124 (29%) are located in Sussex County. All 45 semi-confined wells have geographic coordinates (Figure 1D); 25 (56%) are located in Kent County, 13 (29%) are located in Sussex County, and 7 (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 67 Piedmont wells, fractured-rock wells account for 58 (87%) and karst wells account for 9 (13%) (Figure 2). All 58 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 904 (90%) of 1,000 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 136 ft bls and the 25th and 75th percentiles are 88 and 240 ft bls, respectively. Well depths are not known for 96 (10%) of the wells (Figure 3).

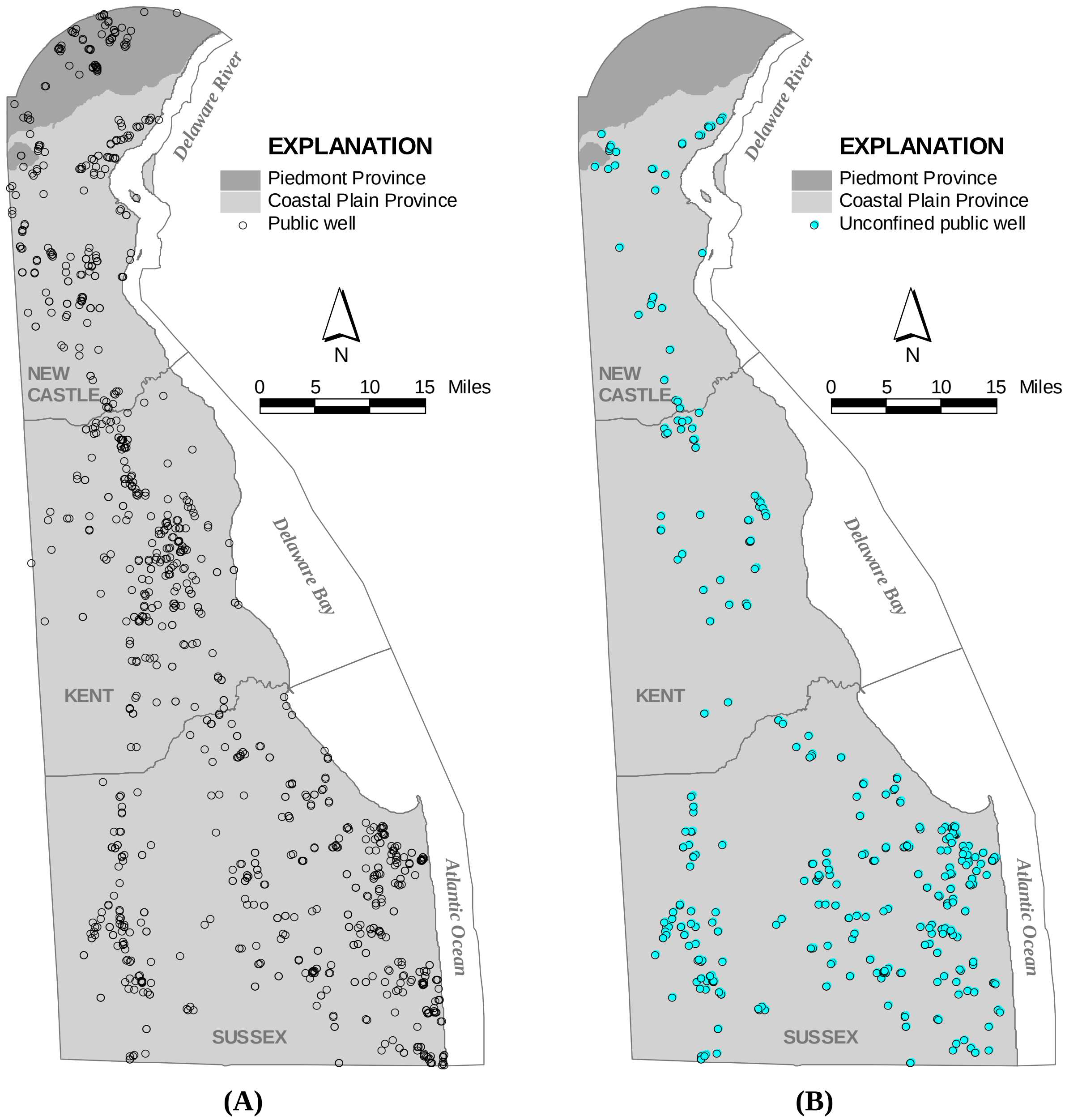


Figure 1. Maps of active public water-supply wells in Delaware – (A) all wells and (B) unconfined wells.

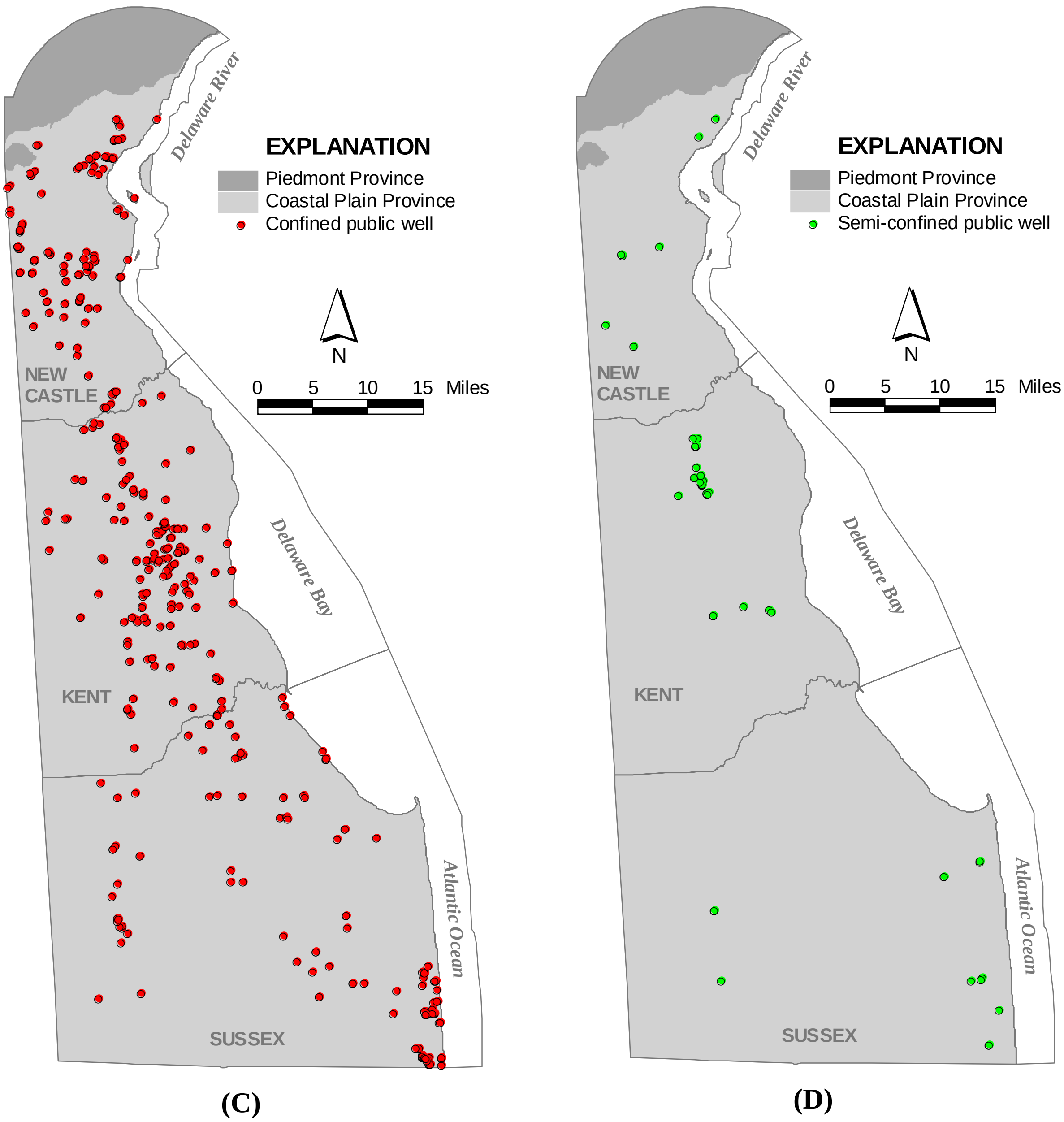


Figure 1. Maps of active public water-supply wells in Delaware (*cont.*) – (C) confined wells and (D) semi-confined wells.

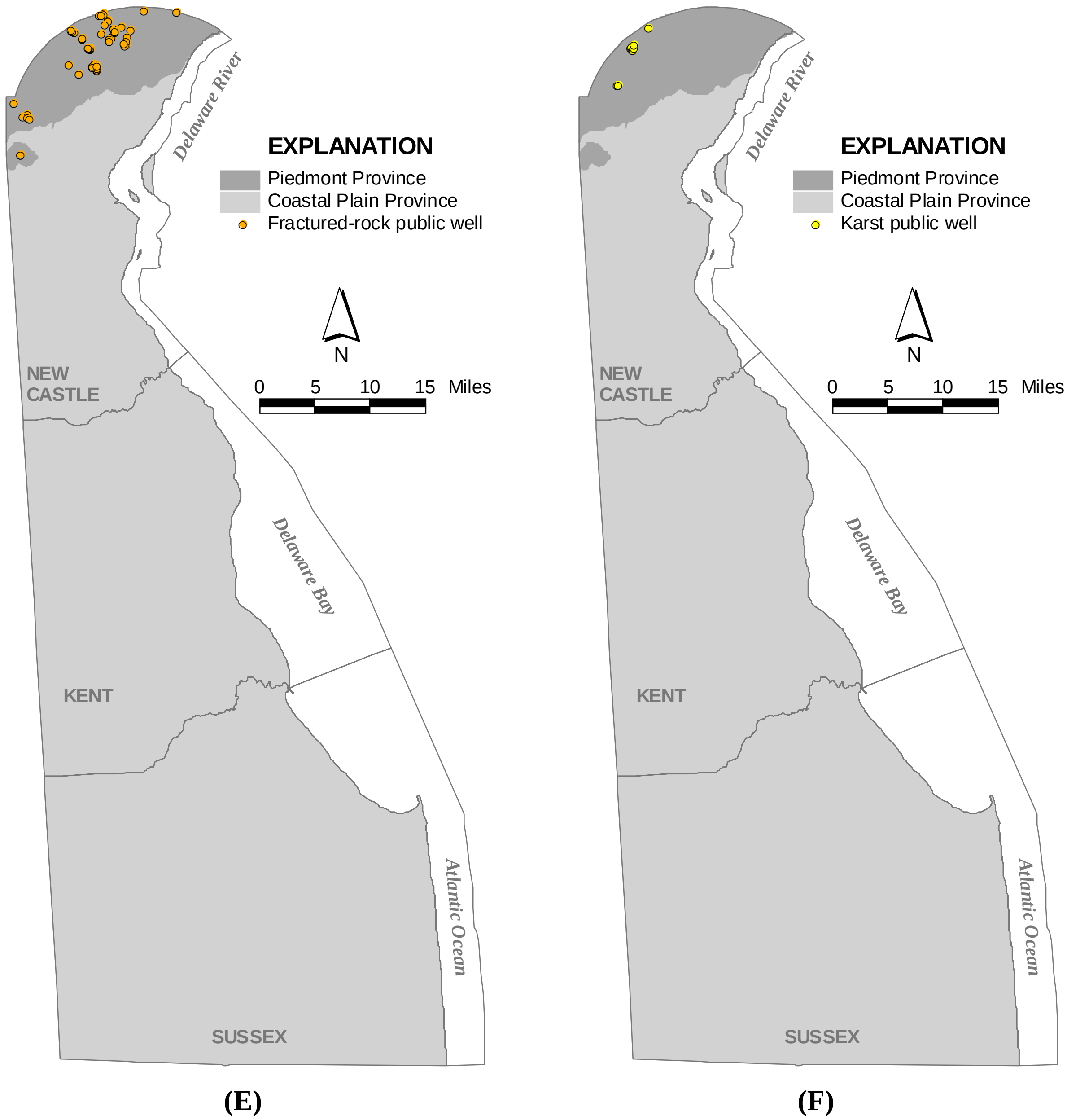


Figure 1. Maps of active public water-supply wells in Delaware (*cont.*) – (E) fractured-rock wells and (F) karst wells.

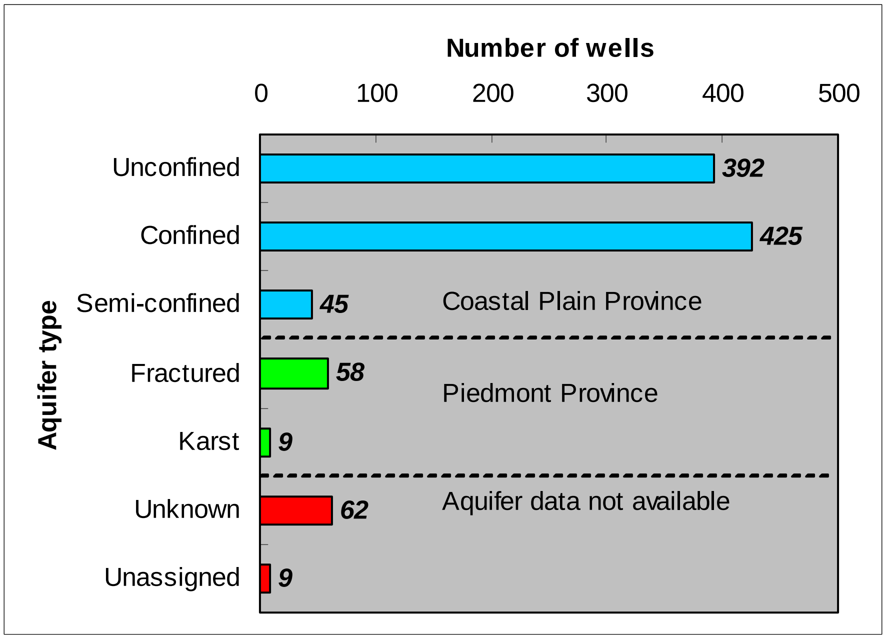


Figure 2. Histogram of active public water-supply wells by aquifer type.

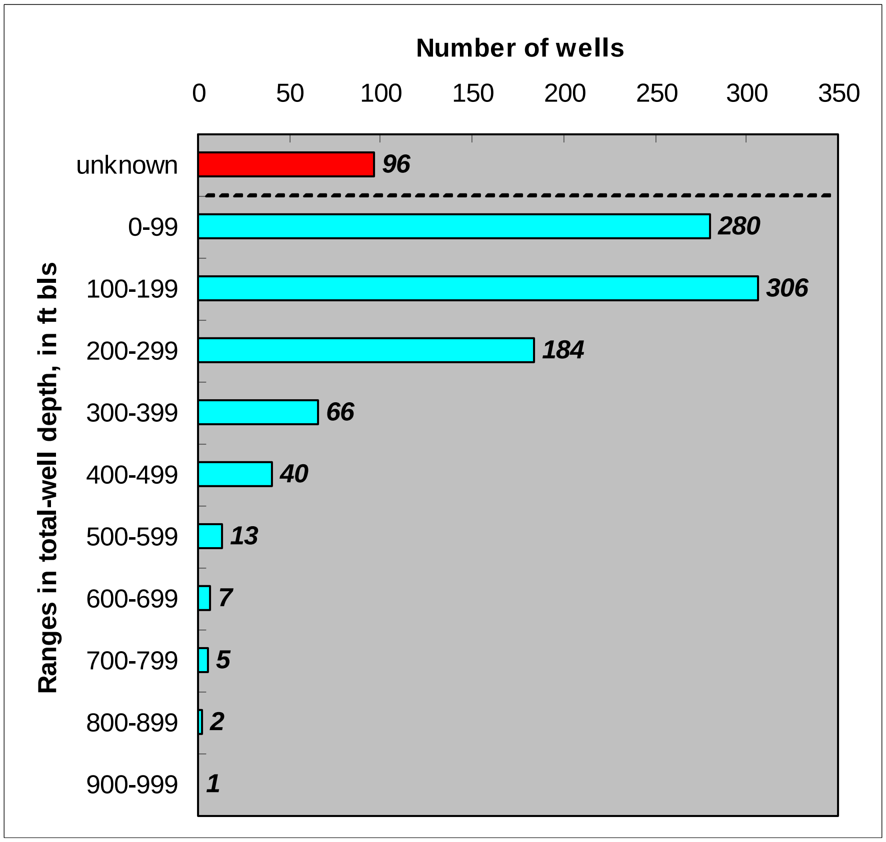


Figure 3. Histogram of active public water-supply wells by ranges in total-well depth.

Results and discussion

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

General chemistry

For this assessment, general ground-water 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, 2006). 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. Some parameters were excluded due to a limited number of analyses (e.g., manganese and sulfate).

Nitrate as nitrogen

Overall, 1,275 nitrate as nitrogen ("nitrate") analyses are in the SDWIS query provided to DNREC. Of these, 172 (14%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 132 nitrate analyses where aquifer type is known (Table 2). This number translates to ~14% of the total number of wells (929) where aquifer type is known (Figure 2). Overall, nitrate concentrations ranged from non detectable to 21.5 mg/L with a median value of 0.1 mg/L (Table 2 and Figure 4). Outliers in Figure 4 (and otherwise in this report) were computed by Grapher using the following equations:

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

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

Nitrate was not detected above the laboratory quantitation limit in 66 (50%) of the 132 analyses (Table 2). Concentrations in 64 (48%) of the samples exceeded 0.4 mg/L (Table 2), a threshold used to distinguish between natural and human-impacted ground water (Hamilton et al., 1993). Nitrate concentrations exceeded the PMCL (10 mg/L) in 7 (5%) of the 132 samples (Table 2). All but one of the PMCL exceedences occurred in Sussex County; the remaining exceedence occurred in southern Kent County (Figures 5a and 5b). Overall, nitrate concentrations decrease with depth and, below depths of ~225 ft bls, nitrate is rarely detected above the quantitation limit (Figure 6).

Unconfined wells account for 41 (31%) of the 132 individual wells/samples linked by DNREC ID (Table 2). This number translates to ~10% of the total number of active unconfined wells (392) statewide (Figure 2). Nitrate was not detected above the laboratory quantitation limit in 4 (10%) of the 41 samples. Concentrations in 36 (88%) of the 41 samples exceeded 0.4 mg/L suggesting that the ground-water quality in the unconfined aquifer is largely affected by human activities. Most of the concentrations below 0.4 mg/L occur in the southeastern portion of Sussex County where ground-water is largely anoxic (Figure 5a; Kasper and Strohmeier, 2007). The most elevated nitrate concentration (21.5 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 (4.7 mg/L) and the lowest percentage of non detects (Table 2). The median concentration is slightly lower than, but comparable to, 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 within one mg/L of 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, however, 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 (Kasper and Strohmeier, 2007). Nitrate exceeded the PMCL in 4 (10%) of the 41 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 ground-water 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 deepest PMCL exceedence (13.3 mg/L) occurred at a depth of 148 ft bls. At 190 ft bls, the deepest unconfined well sample had a nitrate concentration of 4.6 mg/L, well above the 0.4 mg/L threshold indicative of human impacts.

Confined wells account for 74 (56%) of the 132 individual wells/samples linked by DNREC ID (Table 2). This number translates to ~17% of the total number of active confined wells (425) statewide (Figure 2). Nitrate was not detected above the laboratory quantitation limit in 54 (73%) of the 74 samples. However, concentrations in 19 (26%) of the 74 wells exceeded 0.4 mg/L suggesting that the ground-water quality in a significant fraction of confined aquifer wells is susceptible to human activities. Of these, 15 are confined Potomac aquifer wells, all 225-ft deep or shallower, located in the northernmost portion of the Coastal Plain (Figure 5b). Nitrate exceeded the PMCL in 3 (4%) of the 74 samples suggesting either localized or poor confinement or compromised well construction. Two of the PMCL exceedences occurred in Sussex County and the remaining exceedence occurred in Kent County (Figure 5b). PMCL exceedences occurred at depths of 170 ft bls or shallower (Figure 6), indicating that PMCL issues are limited only to relatively shallow confined wells. Nitrate concentrations decrease with depth in confined aquifers and, consistent with the overall trend, are rarely detectable below depths of ~225 ft bls (Figure 6).

Semi-confined wells account for 8 (6%) of the 132 individual wells/samples linked by DNREC ID (Table 2). This number translates to ~18% of the total number of active semi-confined wells (45) statewide (Figure 2). Nitrate was not detected above the laboratory quantitation limit in 6 (75%) of the 8 samples. The nitrate concentration in both of the remaining samples was 3.6 mg/L, below the PMCL. Limited data suggest that semi-confined wells, like some confined wells, are susceptible to human activities.

Fractured-rock wells account for 9 (7%) of the 132 individual wells/samples linked by DNREC ID (Table 2). This number translates to ~16% of the total number of fractured-rock wells (58) statewide (Figure 2). Although data are limited, fractured-rock wells have the second-highest median nitrate concentration (2.7 mg/L; Table 2 and Figure 4). The high percentage of samples with nitrate above 0.4 mg/L (78%) indicates that ground-water quality in the fractured-rock aquifer(s), like the unconfined aquifer, is largely affected by human activities. None of the nitrate concentrations, however, exceeded the PMCL. No nitrate data could be linked by DNREC ID for karst wells (Table 2).

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 (U.S. EPA, 2006).]

STATISTICS	ALL WELLS	UNCONFINED WELLS	CONFINED WELLS	SEMI-CONFINED WELLS	FRACTURED-ROCK WELLS	KARST WELLS
Number of wells/samples (#)	132	41	74	8	9	0
Percent of total (%)	100	31	56	6	7	0
Maximum (mg/L)	21.50	21.50	14.20	3.60	6.20	---
75th percentile (mg/L)	4.63	7.05	1.20	0.90	4.40	---
50th percentile (mg/L)	0.08	4.70	0.00	0.00	2.70	---
25th percentile (mg/L)	0.00	2.57	0.00	0.00	1.60	---
Minimum (mg/L)	0.00	0.00	0.00	0.00	0.00	---
Number not detected (#ND)	66	4	54	6	2	---
Percent not detected (%ND)	50	10	73	75	22	---
Number > 0.4 mg/L (#)	64	36	19	2	7	---
Percent > 0.4 mg/L (%)	48	88	26	25	78	---
Number > 10 mg/L PMCL (#)	7	4	3	0	0	---
Percent > 10 mg/L PMCL (%)	5	10	4	0	0	---

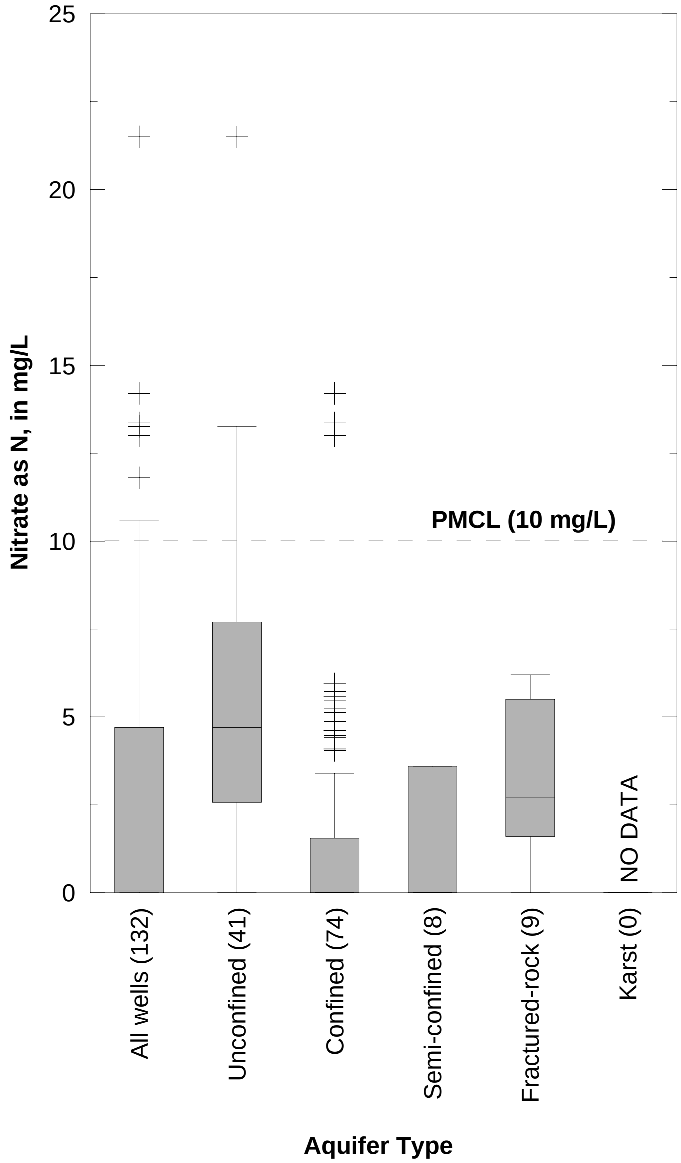


Figure 4. Percentile diagrams of nitrate data by aquifer type. [mg/L, milligrams per liter; crosses, outliers; (#), number of samples; PMCL, primary maximum contaminant level for public water-supply systems (U.S. EPA, 2006).]

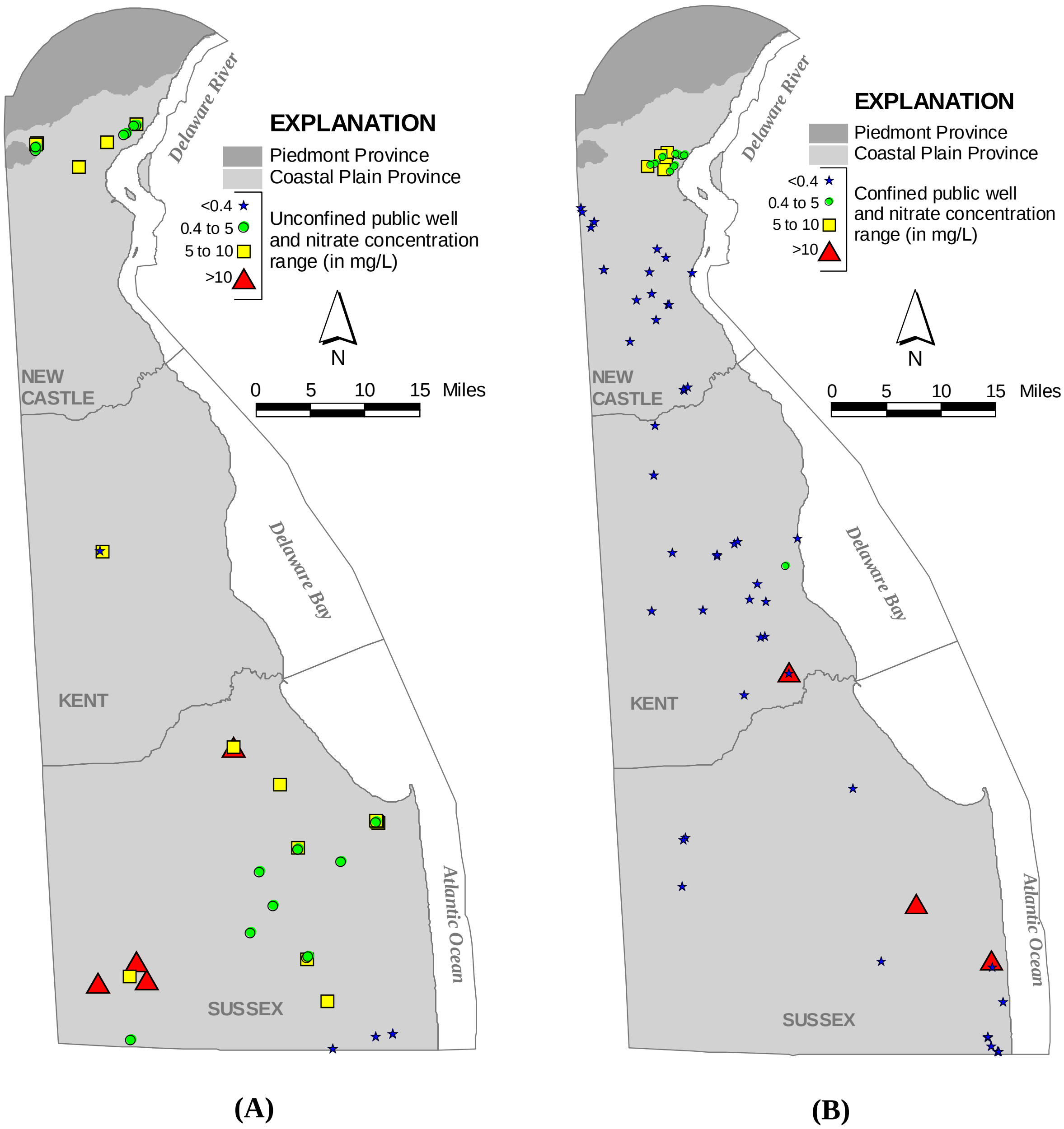


Figure 5. Maps showing nitrate concentration ranges in unconfined (A) and confined (B) public water-supply wells.

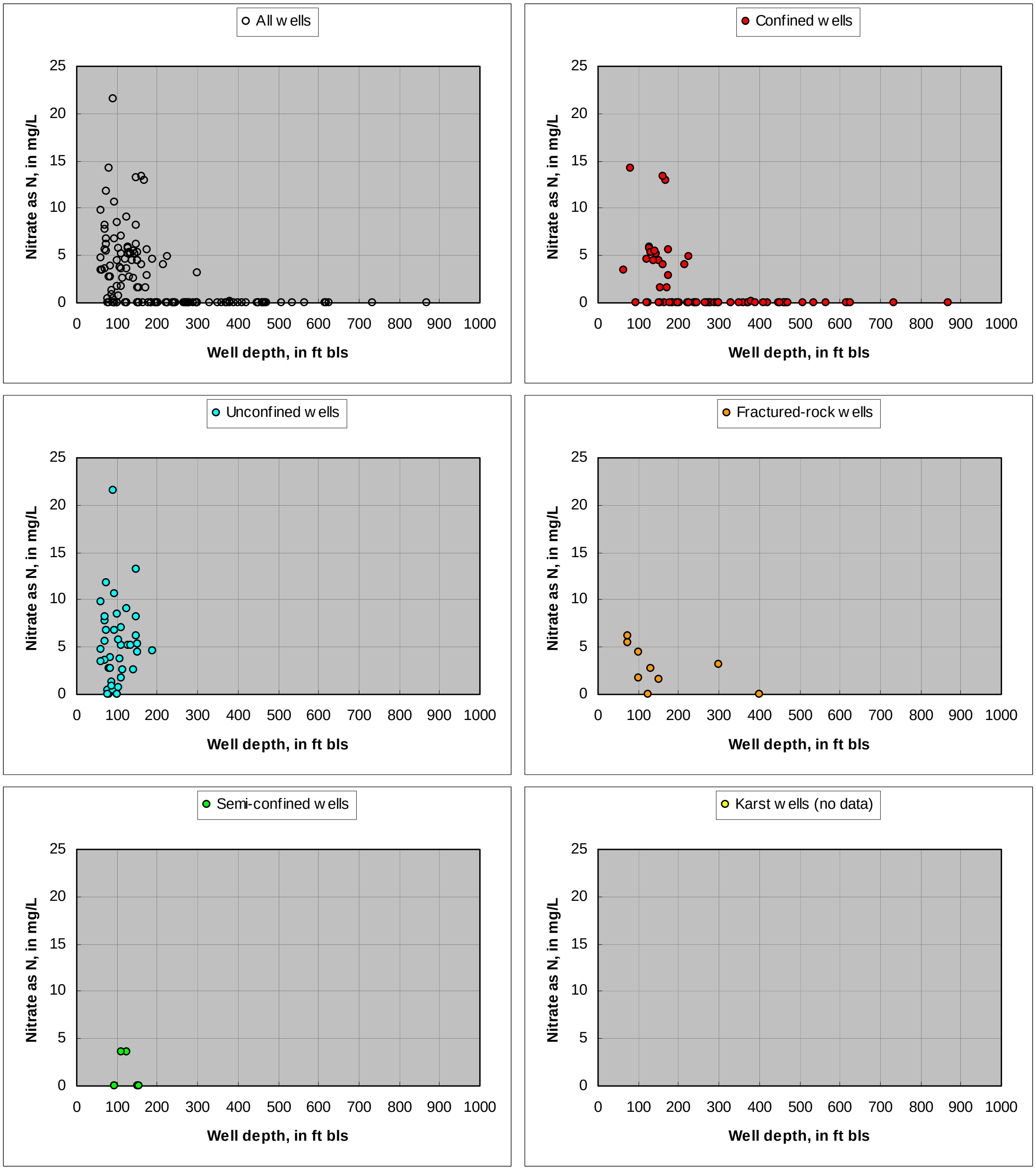


Figure 6. Scatter plots of nitrate versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface.]

Total dissolved solids

Overall, 505 total dissolved solids (TDS) analyses are in the SDWIS query provided to DNREC. Of these, 116 (23%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 101 TDS analyses where aquifer type is known (Table 3). This number translates to ~11% of the total number of wells (929) where aquifer type is known (Figure 2). Overall, TDS concentrations ranged from 12 to 708 mg/L with a median value of 159 mg/L (Table 3 and Figure 7). TDS concentrations exceeded the SMCL (500 mg/L) in 1 (1%) of the 101 samples (Table 3). The single SMCL exceedence was associated with a confined, Pocomoke aquifer well located in coastal Sussex County, Delaware.

Based on 26 samples, the unconfined aquifer had the lowest median TDS concentration (135 mg/L; Table 3 and Figure 7), a value that agrees in general with Ferrari's (2001) median (116 mg/L). Moreover, the range in unconfined well TDS concentrations for this assessment (50 to 274 mg/L) is in general agreement with Ferrari's (2001) range (56 to 221 mg/L). The median TDS concentration for confined wells (156 mg/L) was higher than the median for unconfined wells, and the overall range in TDS was larger. Relatively higher TDS concentrations for the confined aquifers are likely due to longer ground-water contact time with formation sediments. Although data are limited, semi-confined and fractured-rock wells had the highest and second-highest median TDS concentrations (190 and 183 mg/L, respectively). No TDS data could be linked by DNREC ID for karst wells. Overall, there is no apparent trend in TDS with depth (Figure 8).

Table 3. Statistical summary of total dissolved solids (TDS) data by aquifer type. [mg/L, milligrams per liter; ---, no data; SMCL, secondary maximum contaminant level for public water-supply systems (U.S. EPA, 2006).]

STATISTICS	ALL WELLS	UNCONFINED WELLS	CONFINED WELLS	SEMI-CONFINED WELLS	FRACTURED-ROCK WELLS	KARST WELLS
Number of wells/samples (#)	101	26	62	5	8	0
Percent of total (%)	100	26	61	5	8	0
Maximum (mg/L)	708	274	708	250	188	---
75th percentile (mg/L)	194	190	201	198	184	---
50th percentile (mg/L)	159	135	156	190	183	---
25th percentile (mg/L)	113	85	113	163	171	---
Minimum (mg/L)	12	50	12	151	80	---
Number not detected (#ND)	0	0	0	0	0	---
Percent not detected (%ND)	0	0	0	0	0	---
Number > 500 mg/L SMCL (#)	1	0	1	0	0	---
Percent > 500 mg/L SMCL (%)	1	0	2	0	0	---

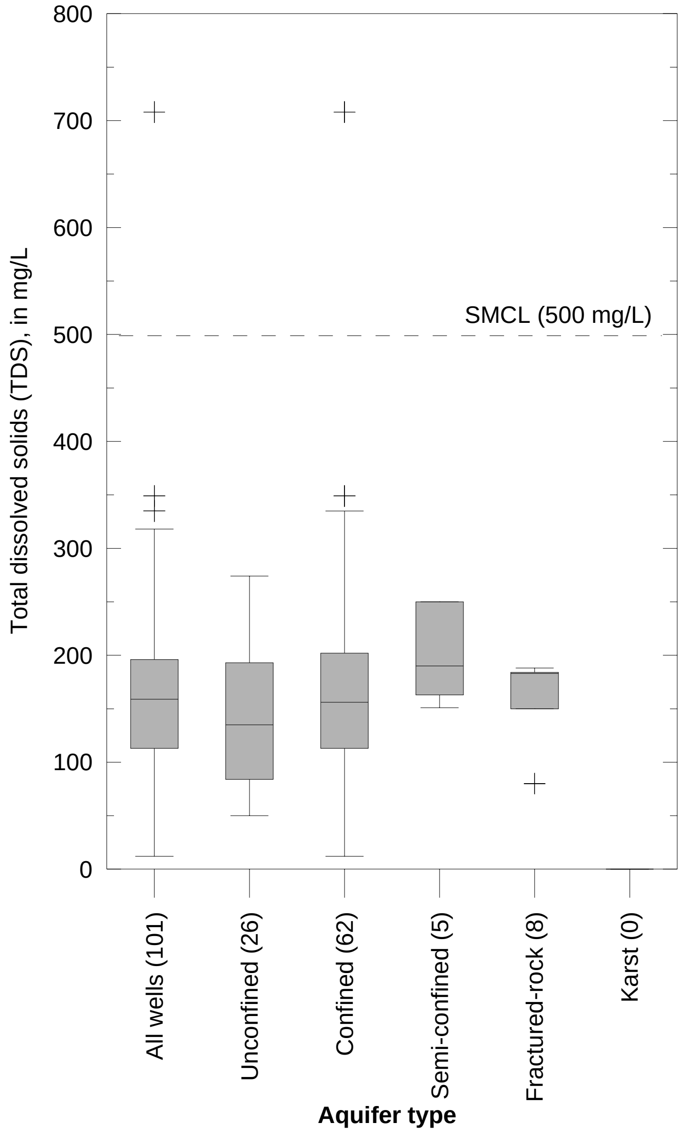


Figure 7. Percentile diagrams of total dissolved solids (TDS) data by aquifer type. [mg/L, milligrams per liter; crosses, outliers; (#), number of samples; SMCL, secondary maximum contaminant level for public water-supply systems (U.S. EPA, 2006).]

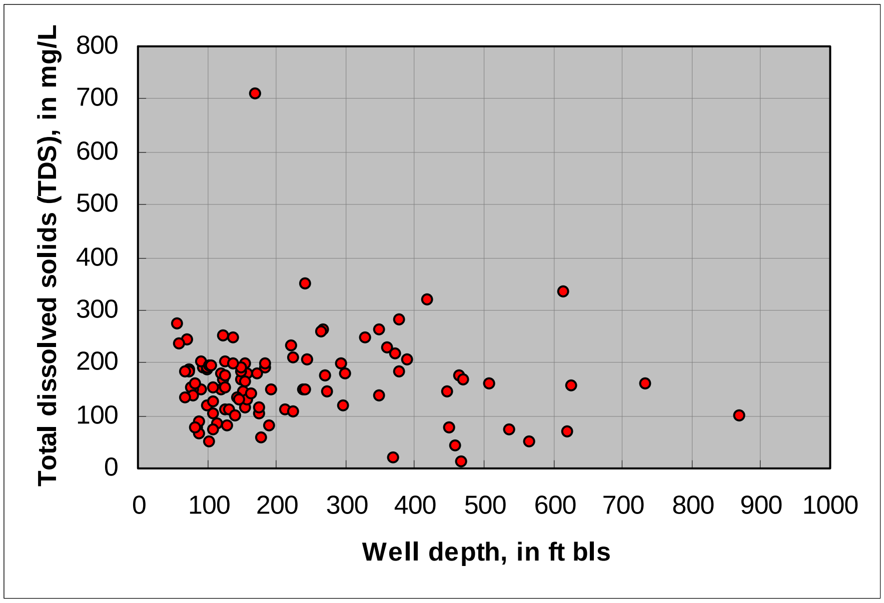


Figure 8. Scatter plot of total dissolved solids (TDS) versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface.]

Chloride

Overall, 748 chloride analyses are in the SDWIS query provided to DNREC. Of these, 151 (20%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 125 chloride analyses where aquifer type is known (Table 4). This number translates to ~13% of the total number of wells (929) where aquifer type is known (Figure 2). Overall, chloride concentrations ranged from 0.7 to 499 mg/L with a median value of 13.3 mg/L (Table 4 and Figure 9). Chloride concentrations exceeded the SMCL (250 mg/L) in 2 (2%) of the 125 samples (Table 4). One of the SMCL exceedences is associated with the previously-mentioned confined, Pocomoke aquifer well with TDS above the SMCL. The remaining and most-elevated chloride concentration (499 mg/L) is associated with a confined, Potomac aquifer well located in northern New Castle County, Delaware. TDS and sodium concentrations for this well (48 and 3.33 mg/L, respectively), however, suggest that the chloride data may be erroneous.

The fractured-rock and unconfined aquifers had the highest median chloride concentrations (19.3 and 18.5 mg/L, respectively; Table 4 and Figure 9), perhaps 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 agreement with Ferrari's (2001) median (18.3 mg/L). Confined and semi-confined wells had the lowest median chloride concentrations (4.8 and 4.5 mg/L, respectively). The two SMCL exceedences were, however, associated with confined wells. No chloride data could be linked by DNREC ID for karst wells. Overall, there is a decreasing trend in chloride with depth (Figure 8). Below depths of ~400 ft bls, chloride was generally less than 10 mg/L excepting one outlier (Figure 10).

Table 4. Statistical summary of chloride data by aquifer type. [mg/L, milligrams per liter; ---, no data; SMCL, secondary maximum contaminant level for public water-supply systems (U.S. EPA, 2006).]

STATISTICS	ALL WELLS	UNCONFINED WELLS	CONFINED WELLS	SEMI-CONFINED WELLS	FRACTURED-ROCK WELLS	KARST WELLS
Number of wells/samples (#)	125	38	70	8	9	0
Percent of total (%)	100	30	56	6	7	0
Maximum (mg/L)	499.0	90.6	499.0	85.1	42.8	---
75th percentile (mg/L)	25.7	37.0	21.3	10.0	37.1	---
50th percentile (mg/L)	13.3	18.5	4.8	4.5	19.3	---
25th percentile (mg/L)	3.3	13.4	2.0	3.3	17.4	---
Minimum (mg/L)	0.7	3.3	0.7	2.1	5.3	---
Number not detected (#ND)	0	0	0	0	0	---
Percent not detected (%ND)	0	0	0	0	0	---
Number > 250 mg/L SMCL (#)	2	0	2	0	0	---
Percent > 250 mg/L SMCL (%)	2	0	3	0	0	---

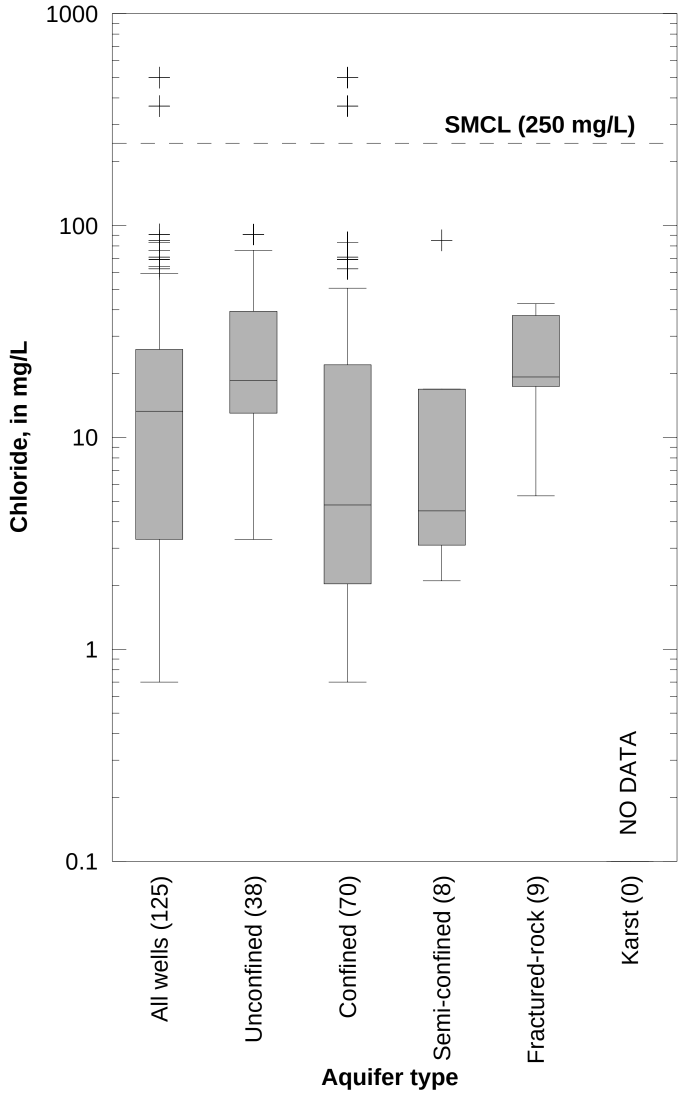


Figure 9. Percentile diagrams of chloride data by aquifer type. [mg/L, milligrams per liter; crosses, outliers; (#), number of samples; SMCL, secondary maximum contaminant level for public water-supply systems (U.S. EPA, 2006).]

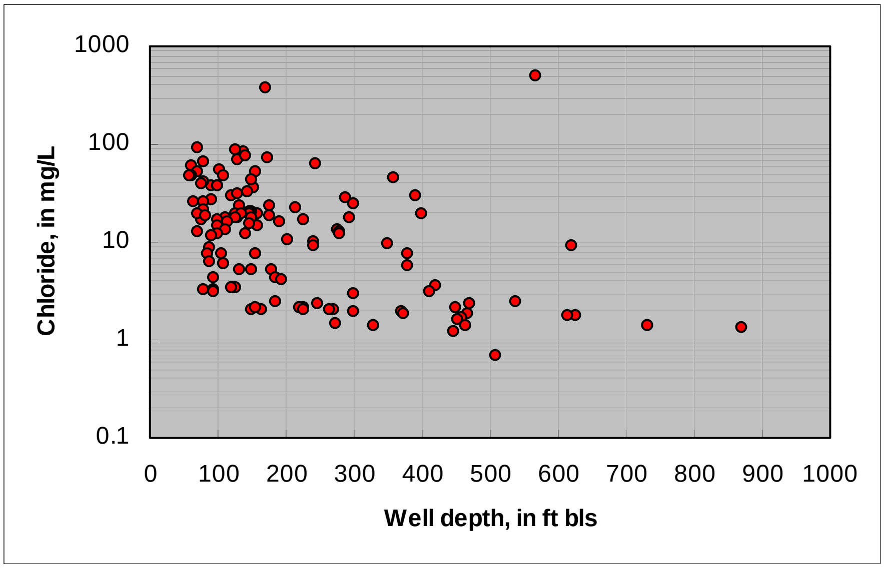


Figure 10. Scatter plot of chloride versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface.]

Sodium

Overall, 770 sodium analyses are in the SDWIS query provided to DNREC. Of these, 153 (20%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 128 sodium analyses where aquifer type is known (Table 5). This number translates to ~14% of the total number of wells (929) where aquifer type is known (Figure 2). Overall, sodium concentrations ranged from 2.4 to 183 mg/L with a median value of 11.8 mg/L (Table 5 and Figure 11). Sodium concentrations exceeded the HA (20 mg/L) in 38 (30%) of the 128 samples (Table 5). The most elevated sodium concentration (183 mg/L) is associated with the previously-mentioned confined, Pocomoke aquifer well with TDS and chloride above their SMCLs.

Similar to the chloride data, the fractured-rock and unconfined aquifers had the highest median sodium concentrations (13.5 and 13.0 mg/L, respectively; Table 5 and Figure 11). The median value for the unconfined aquifer is in agreement with Ferrari's (2001) median (11.7 mg/L). Sodium is a component of the human diet and poultry manure and, therefore, it's presence in shallow aquifers can reflect impacts from wastewater-disposal and agricultural practices (Denver, 1989). Confined and semi-confined aquifers had lower median sodium concentrations (11.4 and 5.6 mg/L, respectively). Confined aquifers, however, had the highest sodium concentrations overall (183 mg/L) and the largest percentage of concentrations above the HA (34%; Table 5 and Figure 11). Out of 5 confined wells with sodium concentrations greater than 100 mg/L, 4 were associated with aquifers that contain the mineral glauconitic (3 Piney Point aquifer wells and 1 Mount Laurel aquifer well; Ramsey, 2005, 2007). Each of these wells also is greater than 400-ft deep (Figure 10). Elevated sodium concentrations in ground water from glauconitic aquifers are the result of ion-exchange processes (Spoljaric, 1986). No sodium data could be linked by DNREC ID for karst wells. Overall, 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; ---, no data; HA, health advisory (U.S. EPA, 2006).]

STATISTICS	ALL WELLS	UNCONFINED WELLS	CONFINED WELLS	SEMI-CONFINED WELLS	FRACTURED-ROCK WELLS	KARST WELLS
Number of wells/samples (#)	128	37	74	8	9	0
Percent of total (%)	100	29	58	6	7	0
Maximum (mg/L)	183.0	41.8	183.0	46.0	23.9	---
75th percentile (mg/L)	22.7	21.2	27.8	7.9	15.5	---
50th percentile (mg/L)	11.8	13.0	11.4	5.6	13.5	---
25th percentile (mg/L)	7.8	9.4	7.5	5.2	11.6	---
Minimum (mg/L)	2.4	5.7	2.4	3.7	5.5	---
Number not detected (#ND)	0	0	0	0	0	---
Percent not detected (%ND)	0	0	0	0	0	---
Number > 20 mg/L HA (#)	38	10	25	1	2	---
Percent > 20 mg/L HA (%)	30	27	34	13	22	---

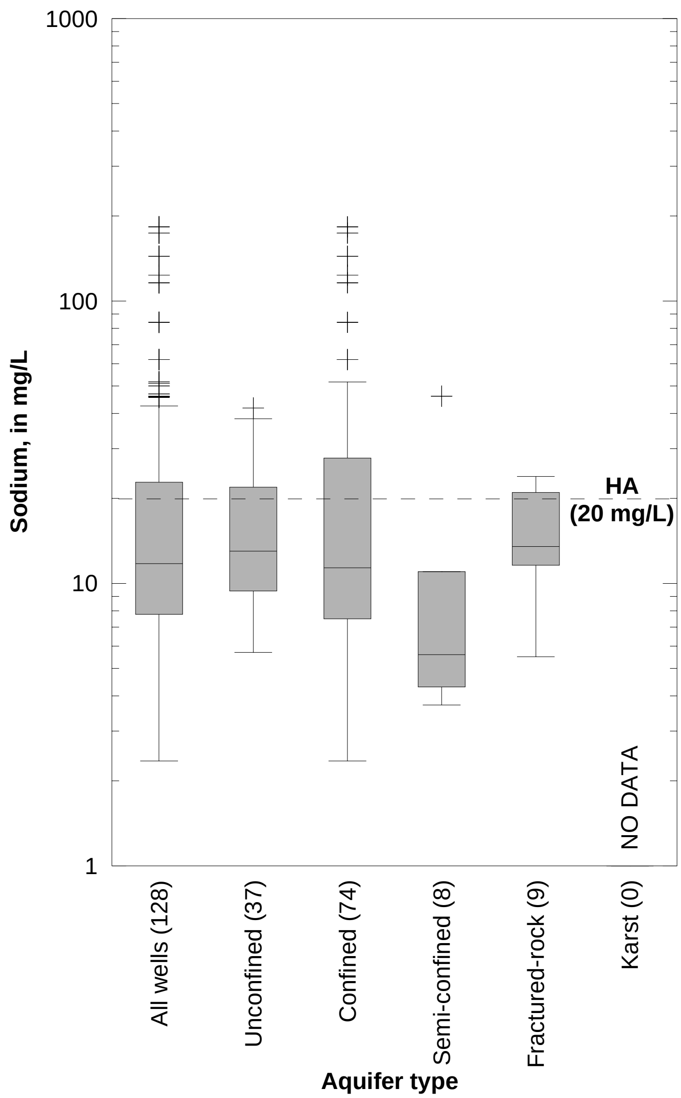


Figure 11. Percentile diagrams of sodium data by aquifer type. [mg/L, milligrams per liter; crosses, outliers; (#), number of samples; HA, health advisory for public water-supply systems (U.S. EPA, 2006).]

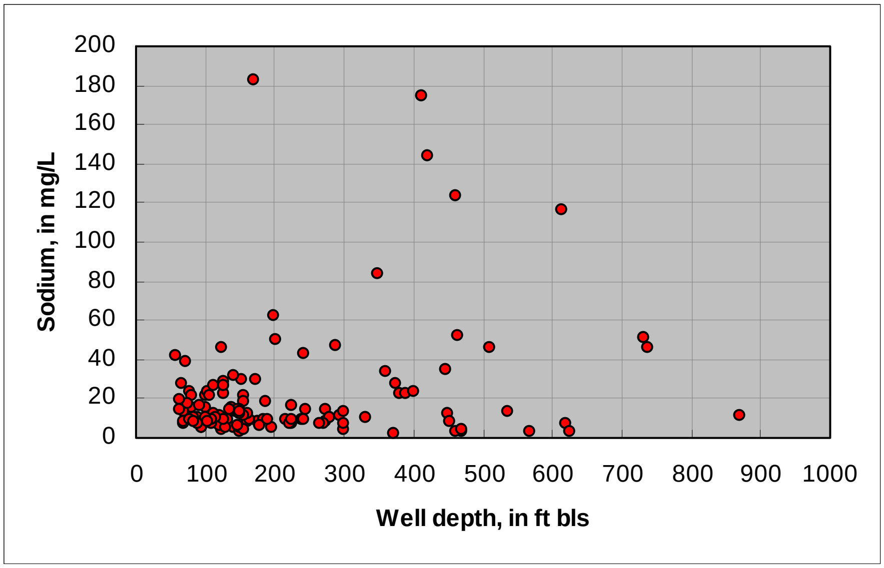


Figure 12. Scatter plot of sodium versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface.]

Iron

Overall, 866 iron analyses are in the SDWIS query provided to DNREC. Of these, 232 (27%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 131 iron analyses where aquifer type is known (Table 6). This number translates to ~14% of the total number of wells (929) where aquifer type is known (Figure 2). Overall, iron concentrations ranged from non detectable to 20.1 mg/L with a median value of 0.08 mg/L (Table 6 and Figure 13). Iron was not detected above the laboratory quantitation limit in 32 (24%) of the 131 analyses. Iron concentrations exceeded the SMCL (0.3 mg/L) in 46 (35%) of the 131 samples (Table 6). The most elevated iron concentration (20.1 mg/L) is associated with a confined, Manokin aquifer well in Sussex County.

Semi-confined and confined aquifers had the highest median iron concentrations (0.25 and 0.12 mg/L, respectively) and the largest percentages of SMCL exceedences (50 and 40%, respectively; Table 6 and Figure 13). Fractured-rock and unconfined aquifers, in contrast, had lower median iron concentrations (0.01 and 0.05 mg/L, respectively) and smaller percentages of concentrations above the SMCL (11 and 27%, respectively). The unconfined aquifer had the largest percentage of non detects (41%) and the range in iron concentrations (not detected to 9.24 mg/L) was within the range reported by Ferrari (2001; not detected to 10.1 mg/L). Iron data for this assessment, however, indicate a higher percentage of SMCL exceedences (27%) than Ferrari (2001; 17%). No iron data could be linked by DNREC ID for karst wells. 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; ---, no data; SMCL, secondary maximum contaminant level for public water-supply systems (U.S. EPA, 2006).]

STATISTICS	ALL WELLS	UNCONFINED WELLS	CONFINED WELLS	SEMI-CONFINED WELLS	FRACTURED-ROCK WELLS	KARST WELLS
Number of wells/samples (#)	131	37	77	8	9	0
Percent of total (%)	100	28	59	6	7	0
Maximum (mg/L)	20.10	9.24	20.10	3.38	1.17	---
75th percentile (mg/L)	0.94	0.41	1.17	1.24	0.07	---
50th percentile (mg/L)	0.08	0.05	0.12	0.25	0.01	---
25th percentile (mg/L)	0.00	0.00	0.01	0.12	0.00	---
Minimum (mg/L)	0.00	0.00	0.00	0.01	0.00	---
Number not detected (#ND)	32	15	14	0	3	---
Percent not detected (%ND)	24	41	18	0	33	---
Number > 0.3 mg/L SMCL (#)	46	10	31	4	1	---
Percent > 0.3 mg/L SMCL (%)	35	27	40	50	11	---

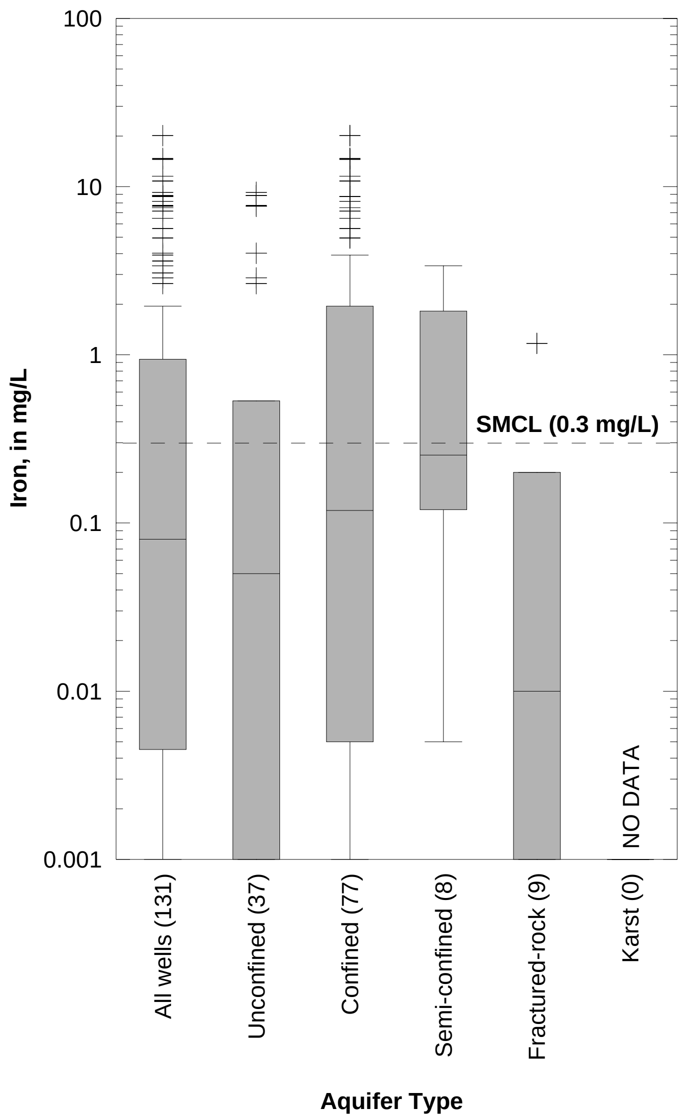


Figure 13. Percentile diagrams of iron data by aquifer type. [mg/L, milligrams per liter; crosses, outliers; (#), number of samples; SMCL, secondary maximum contaminant level for public water-supply systems (U.S. EPA, 2006); non detects assigned values of 0.001 mg/L to allow display on semi-logarithmic plot.]

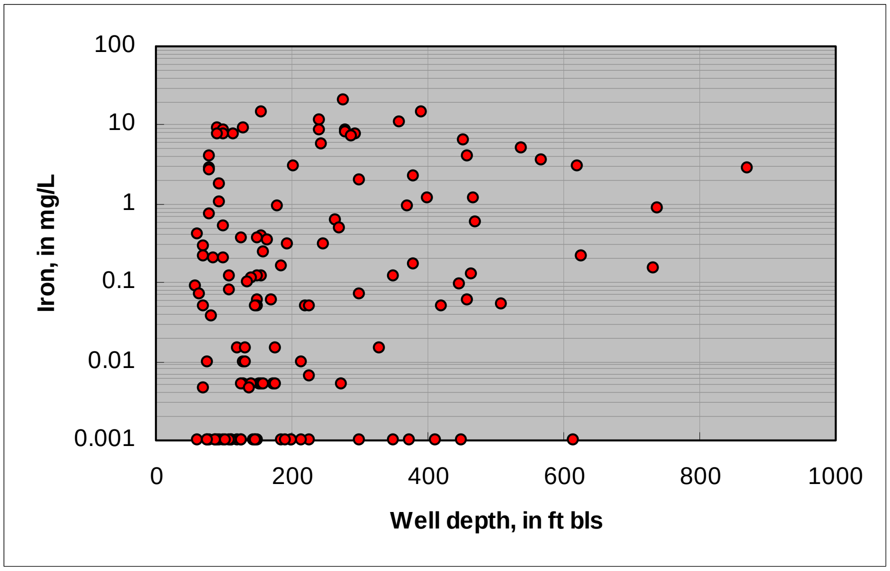


Figure 14. Scatter plot of iron versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface; non detects assigned values of 0.001 mg/L to allow display on semi-logarithmic plot.]

Hardness as $CaCO_3$

Overall, 502 hardness as $CaCO_3$ ("hardness") analyses are in the SDWIS query provided to DNREC. Of these, 119 (24%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 102 hardness analyses where aquifer type is known (Table 7). This number translates to ~11% of the total number of wells (929) where aquifer type is known (Figure 2). Overall, hardness concentrations ranged from non detectable to 205 mg/L with a median value of 63 mg/L (Table 7 and Figure 15). Hardness was not detected above the laboratory quantitation limit in 5 (5%) of the 102 analyses. With respect to the hardness scale of Love (1962), most of the analyses (94 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%). The two analyses with very-hard classifications were associated with confined, Mount Laurel aquifer wells located in southern New Castle County.

Semi-confined and confined aquifers had the highest median hardness concentrations (83.5 and 77.4 mg/L, respectively). Unconfined and fractured-rock and aquifers, in contrast, had lower median hardness concentrations (20.9 and 45.0 mg/L, respectively) with most of the analyses classified as soft (75 and 89%, respectively). No hardness data could be linked by DNREC ID for karst wells. Overall, there is no apparent trend in hardness depth (Figure 16). At depths shallower than 100 ft bls, however, ground water was 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; ---, no data; hardness scale after Love (1962).]

STATISTICS	ALL WELLS	UNCONFINED WELLS	CONFINED WELLS	SEMI-CONFINED WELLS	FRACTURED-ROCK WELLS	KARST WELLS
Number of wells/samples (#)	102	28	60	5	9	0
Percent of total (%)	100	27	59	5	9	0
Maximum (mg/L)	205.0	123.0	205.0	115.0	63.9	---
75th percentile (mg/L)	89.0	57.5	100.3	103.4	45.8	---
50th percentile (mg/L)	63.0	20.9	77.4	83.5	45.0	---
25th percentile (mg/L)	25.4	8.2	49.0	80.9	32.8	---
Minimum (mg/L)	0.0	0.0	0.0	53.0	25.7	---
Number not detected (#ND)	5	3	2	0	0	---
Percent not detected (%ND)	5	11	3	0	0	---
Soft; 0-60 mg/L (#)	50	21	20	1	8	---
Soft; 0-60 mg/L (%)	49	75	33	20	89	---
Mod. hard; 61-120 mg/L (#)	44	6	33	4	1	---
Mod. hard; 61-120 mg/L (%)	43	21	55	80	11	---
Hard; 121-180 mg/L (#)	6	1	5	0	0	---
Hard; 121-180 mg/L (%)	6	4	8	0	0	---
Very hard; >180 mg/L (#)	2	0	2	0	0	---
Very hard; >180 mg/L (%)	2	0	3	0	0	---

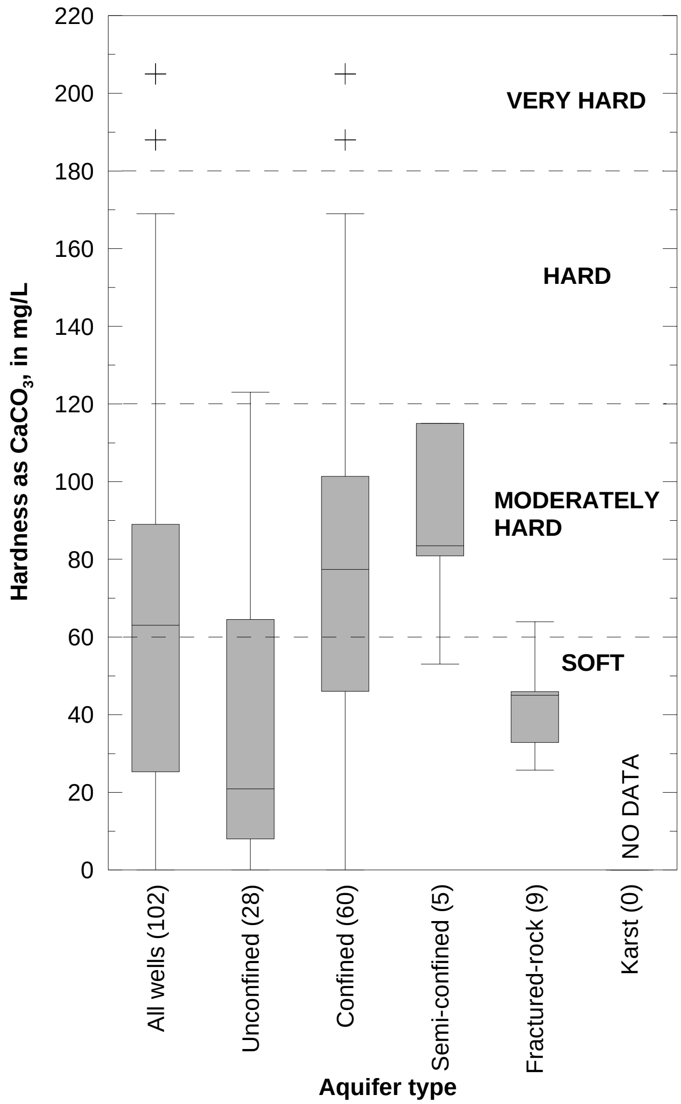


Figure 15. Percentile diagrams of hardness data by aquifer type. [mg/L, milligrams per liter; crosses, outliers; (#), number of samples; hardness scale after Love (1962).]

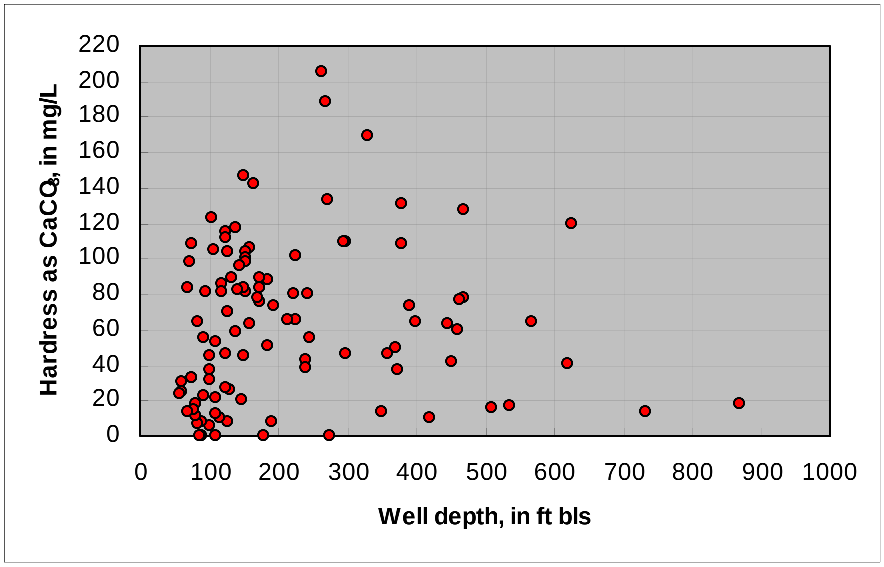


Figure 16. Scatter plot of hardness versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface.]

pH

Overall, 851 pH analyses are in the SDWIS query provided to DNREC. Of these, 148 (17%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 118 pH analyses where aquifer type is known (Table 8). This number translates to ~13% of the total number of wells (929) where aquifer type is known (Figure 2). Overall, pH ranged from 4.7 to 8.4 standard units (S.U.) with a median value of 6.2 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 73 (62%) of the 118 samples (Table 8). None of the pH values exceeded the upper limit of the SMCL range.

Unconfined and fractured-rock aquifers had the lowest median pH values (5.8 and 6.1 S.U., respectively) and the largest percentages of values below 6.5 S.U. (97 and 89%, respectively; Table 8 and Figure 17). Semi-confined and confined aquifers, in contrast, had higher and more neutral median pH values (7.3 and 6.7 S.U., respectively) and lower percentages of values below 6.5 S.U. (29 and 41%, respectively). Most of Delaware's confined aquifers occur in sediments deposited in marine environments. These deposits often contain shell beds, and calcium carbonate from the dissolution of shell material buffers the pH of ground water recharging these aquifers. No pH data could be linked by DNREC ID for karst wells. Overall, pH values below 6.5 S.U. occurred at nearly all depths; the lowest values (<6 S.U.), however, occurred at depths of 200 ft bls or shallower (Figure 18). There appears to be an abrupt change in geochemical environment at this depth as indicated by the pH data.

Table 8. Statistical summary of pH data by aquifer type. [S.U., standard units; ---, no data; SMCL, secondary maximum contaminant level for public water-supply systems (U.S. EPA, 2006).]

STATISTICS	ALL WELLS	UNCONFINED WELLS	CONFINED WELLS	SEMI-CONFINED WELLS	FRACTURED-ROCK WELLS	KARST WELLS
Number of wells/samples (#)	118	38	64	7	9	0
Percent of total (%)	100	37	63	7	9	0
Maximum (S.U.)	8.4	6.7	8.4	8.4	7.4	---
75th percentile (S.U.)	7.4	6.1	7.8	8.1	6.2	---
50th percentile (S.U.)	6.2	5.8	6.7	7.3	6.1	---
25th percentile (S.U.)	5.8	5.3	6.2	6.6	6.0	---
Minimum (S.U.)	4.7	4.7	5.2	5.9	5.8	---
pH <6.5 SMCL (#)	73	37	26	2	8	---
pH <6.5 SMCL (%)	62	97	41	29	89	---
pH 6.5 to 8.5 (#)	45	1	38	5	1	---
pH 6.5 to 8.5 (%)	38	3	59	71	11	---
pH >8.5 SMCL (#)	0	0	0	0	0	---
pH >8.5 SMCL (%)	0	0	0	0	0	---

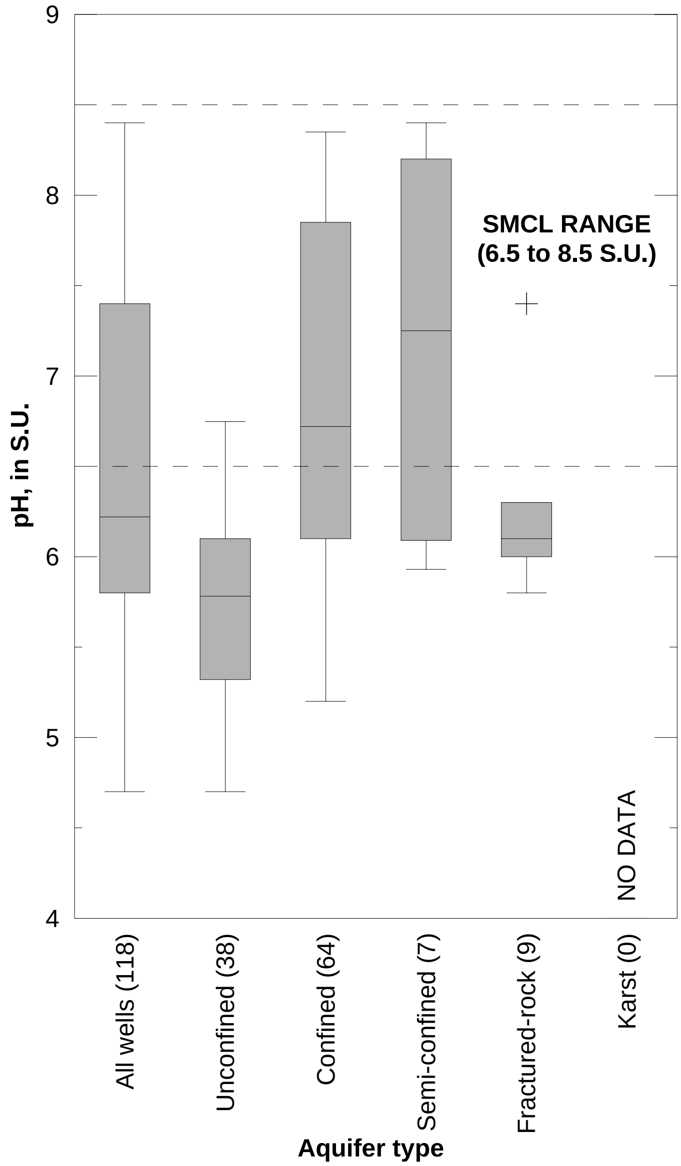


Figure 17. Percentile diagrams of pH data by aquifer type. [S.U., standard units; crosses, outliers; (#), number of samples; SMCL, secondary maximum contaminant level for public water-supply systems (U.S. EPA, 2006).]

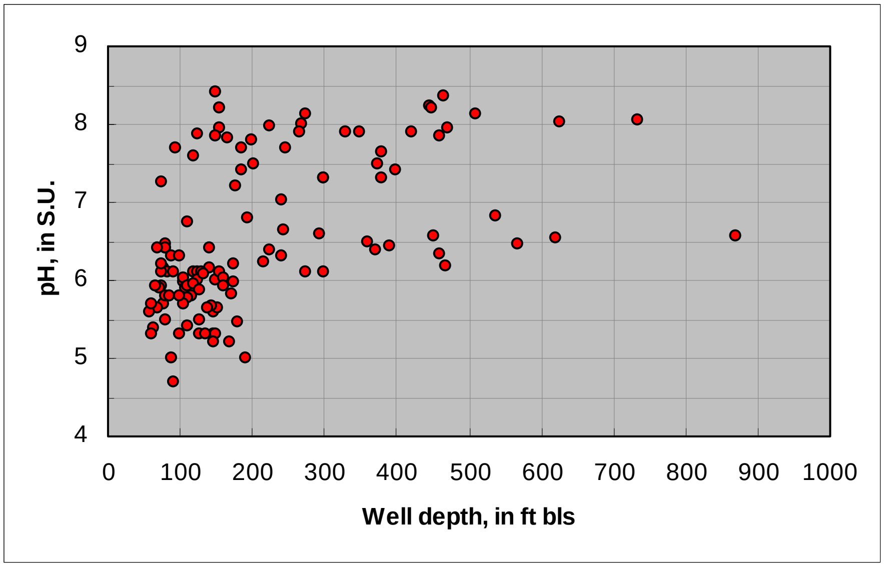


Figure 18. Scatter plot of pH versus well depth. [S.U., standard units; ft bls, feet below land surface.]

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, 51,502 OC analyses are in the SDWIS query provided to DNREC. Duplicate analyses for individual wells were averaged resulting in 10,875 OC analyses. OCs were not detected in 10,621 (98%) of the 10,875 analyses. Out of the 61 organic compounds analyzed, 34 (56%) were detected (Figure 19).

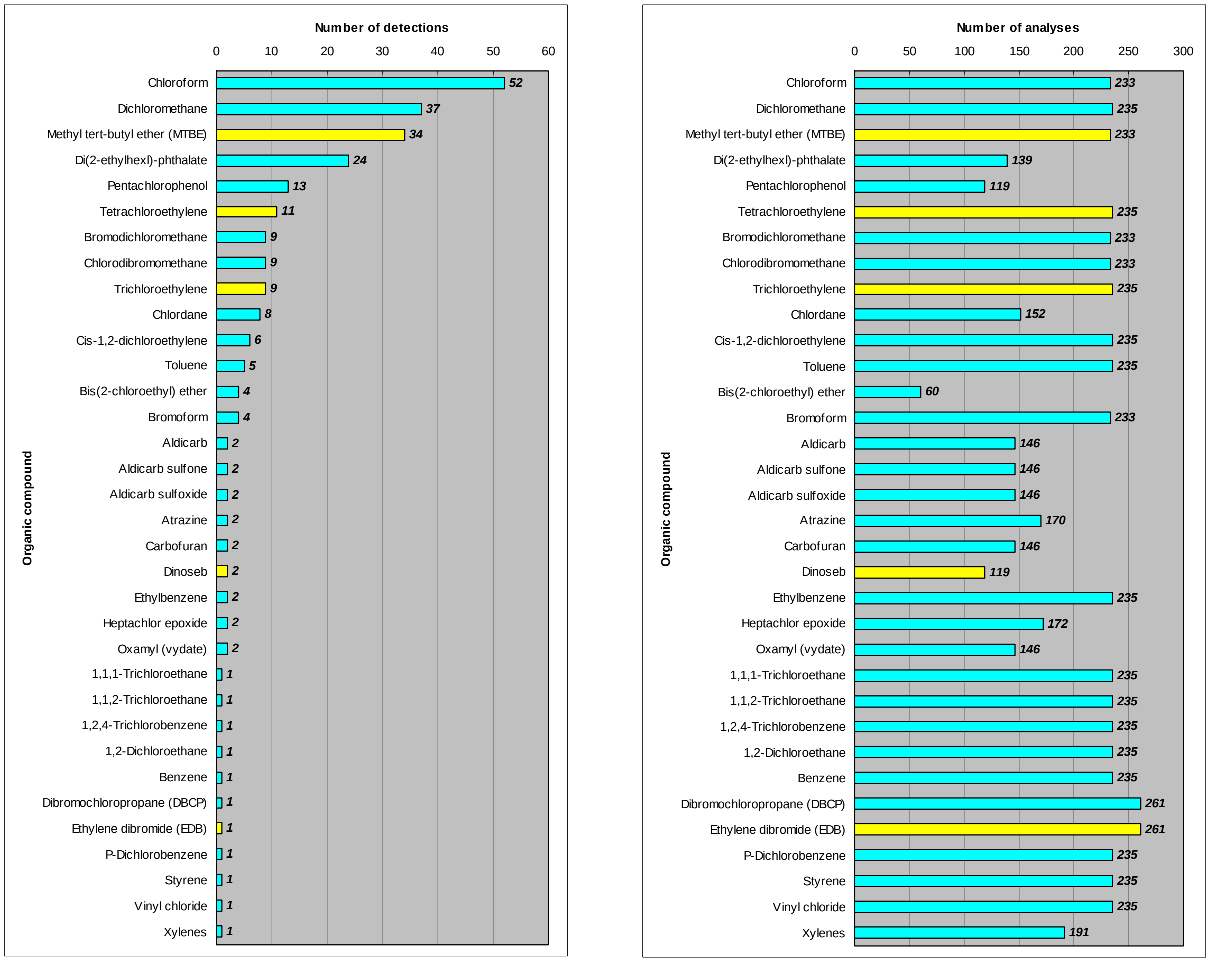
Of the 254 OC detections, about half (133 or 52%) were found at concentrations less than 1 µg/L. Chloroform and dichloromethane, both disinfection byproducts (Ferrari, 2001), were the two most-frequently detected OCs (Figure 19). Methy tert-butyl ether (MTBE), a gasoline additive, was the third most-frequently detected OC (Figure 19), consistent with Ferrari's (2001) study of 30 unconfined public water-supply wells in Delaware.

Of the 34 MTBE detections (Figure 19), aquifer type could be established for 16 wells/samples. Of these, 9 detections were associated with unconfined wells and the remaining 7 were associated with confined or semi-confined wells in the Potomac aquifer system. The Potomac is an extremely heterogeneous fluvial aquifer system used most heavily in the northern, most populated portion of the State (McKenna et al., 2004). Even at low concentrations, evidence of MTBE in confined or semi-confined Potomac wells may be an indication of heterogeneity, confining-bed integrity, and (or) well construction. The data may also reflect the fact that these wells are situated in the most urbanized portion of the state.

PMCLs were exceeded in 11 (0.1%) of the 10,875 analyses. The following five analytes were found above the PMCL: methyl tert-butyl ether (MTBE; 3 exceedences), trichloroethylene (TCE; 3 exceedences), tetrachloroethylene (PCE; 3 exceedences), ethylene dibromide (EDB; 1 exceedence), and dinoseb (1 exceedence). Aquifer type was established for 6 of the 11 samples with PMCL exceedences. Of these, five PMCL exceedences were associated with unconfined wells and one was associated with a confined well. This finding, albeit limited, further illustrates the susceptibility of Delaware's unconfined aquifer, but also indicates that even confined aquifers in the state are susceptible to contamination.

MTBE, TCE, and PCE are within the top ten most frequently detected OCs (Figure 19), consistent with Ferrari's (2001) findings. Well depths were established for 84 MTBE, 85 TCE, and 85 PCE analyses. Scatter plots of MTBE, TCE, and PCE concentrations versus well depth (Figure 20) indicate that these analytes were not detected below depths of ~200 ft bls. This finding is consistent with trends of nitrate versus well depth (Figure 5), and appears to provide another indication of the vertical extent of human impact on ground-water quality in Delaware.

Due to the frequency of MTBE detections (Figure 19), 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, 25 MTBE analyses could be linked by DNREC ID. Of these, MTBE was detected in 9 (36%) of the analyses. More than half of the detections (5 or 56%) are associated with unconfined wells in northern New Castle County (Figure 21a). The 2 detections in Kent County were associated with a single water system, as were the 2 detections in Sussex County. For confined wells, 54 MTBE analyses could be linked by DNREC ID. Of these, MTBE was detected in 6 (11%) of the analyses, and all of the detections were associated with wells located in northern New Castle County (Figure 21b).



(A) **(B)**

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

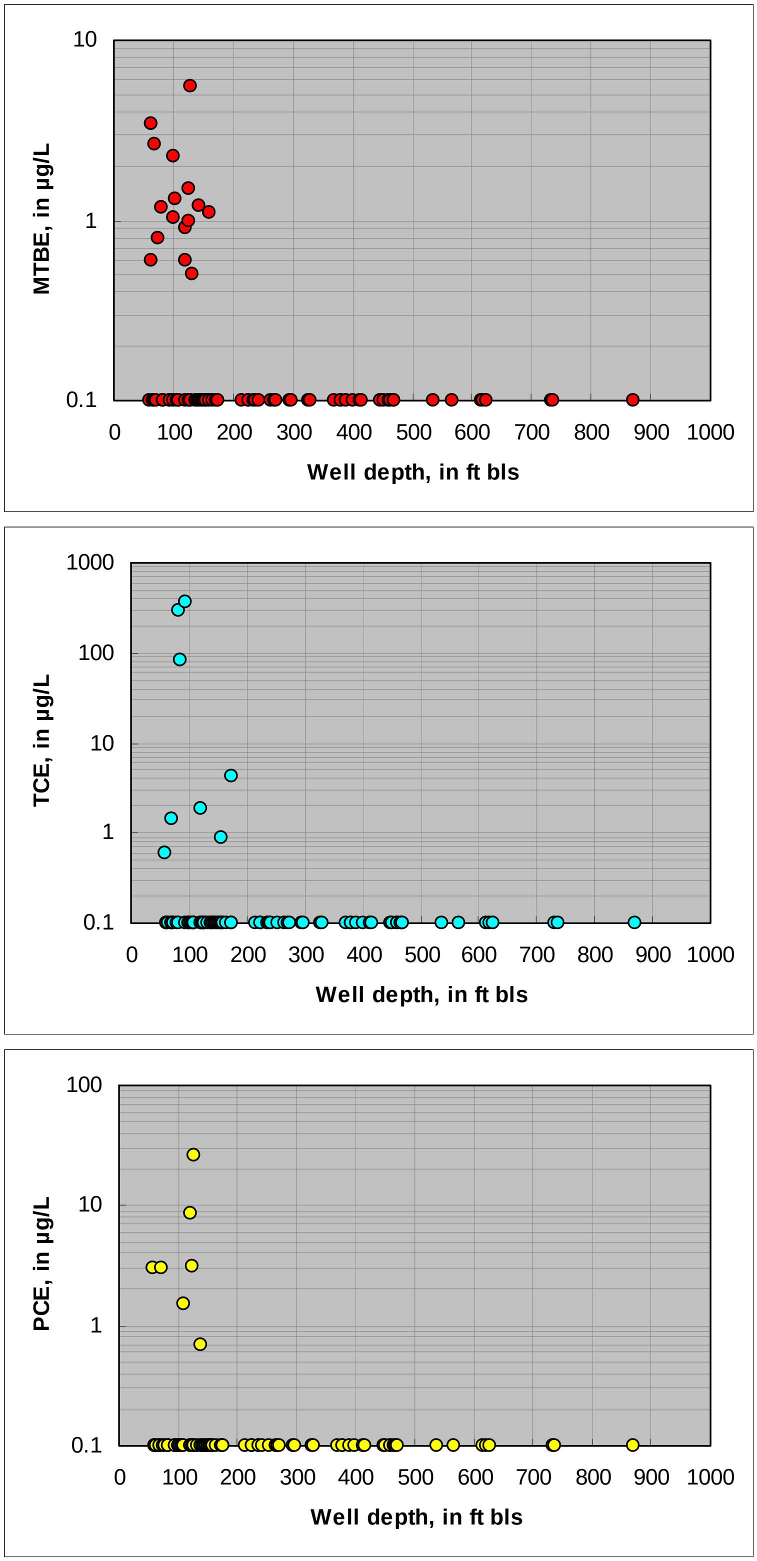


Figure 20. Scatter plots of methyl tert-butyl ether (MTBE), trichloroethylene (TCE), and tetrachloroethylene (PCE) versus well depth. [µg/L, micrograms per liter; ft bls, feet below land surface; PMCLs: MTBE (10 µg/L), TCE (5 µg/L), and PCE (5 µg/L); non-detectable concentrations (zeros) assigned values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

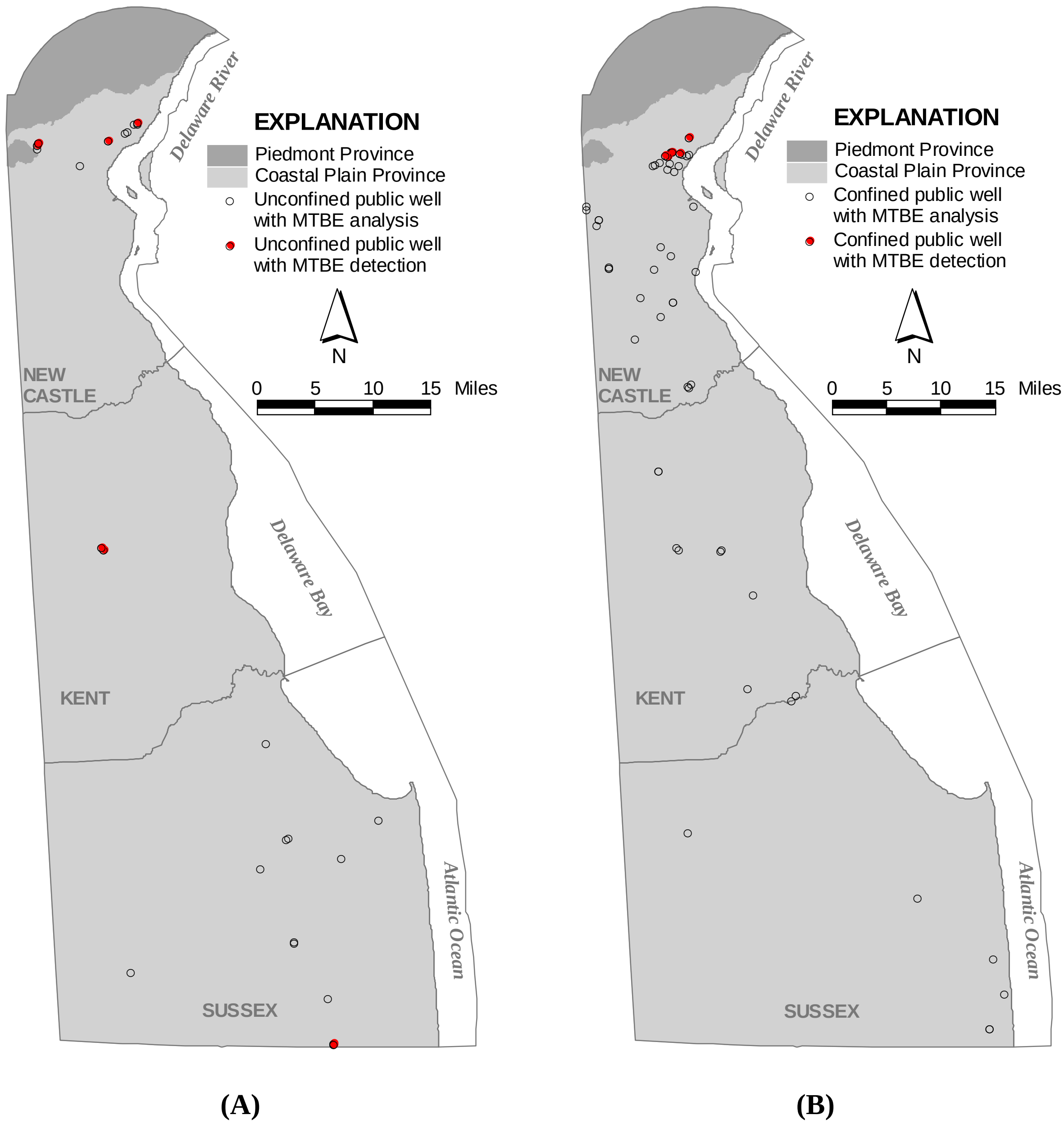


Figure 21. Maps showing methyl tert-butyl ether (MTBE) analyses and detections in unconfined (A) and confined (B) public water-supply wells.

Trace elements

For this assessment, trace elements are limited to the following analytes with PMCLs (DHSS, 2005; U.S. EPA, 2006): 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, 2006).) Overall, 3,440 trace-element analyses are in the SDWIS query provided to DNREC.

Duplicate analyses for individual wells were averaged resulting in 2,769 trace-element analyses. Trace elements were not detected in 2,082 (75%) of the 2,769 analyses.

Detectable trace-element concentrations were less than 0.1 mg/L in 492 (72%) of the 687 detections and less than 1 mg/L in 682 (99%) of the 687 detections. Barium and nickel were the two most-frequently detected trace elements (Figure 22). (Although fluoride had the highest number of detections (161), it was detected in a relatively small percentage (35%) of the 459 analyses (Figure x).) Barium was detected 143 (74%) of the 194 analyses and nickel was detected in 115 (60%) of 193 analyses (Figure 22).

PMCLs or action levels were exceeded in 15 (0.5%) of the 2,769 analyses. The following four analytes were found above the PMCL or action level: lead (11 exceedences), thallium (2 exceedences), antimony (1 exceedence), and chromium (1 exceedence). Aquifer type was established for 5 of the 15 samples with PMCL or action-level exceedences; these included 4 lead exceedences and one chromium exceedence. The lead exceedences involved 2 confined, 1 semi-confined, and 1 unconfined well. The single chromium exceedence was associated with a confined, Frederica aquifer well located in Sussex County, Delaware.

The fate, transport, and remediation of arsenic in Delaware soil are topics of recent investigation and scrutiny (DNREC, 2005; Sparks et al., 2007). Published data on arsenic in Delaware's ground water are generally lacking, however, and limited to the surficial aquifer system (see, for e.g., Denver et al., 2004). Sources of arsenic in ground water 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). Although published results are not currently available, an ongoing study of Maryland's Coastal-Plain aquifers will include the results of several thousand ground-water samples with arsenic analyses (David W. Bolton, Maryland Geological Survey, written communication, September 10, 2008). Because the hydrogeologic frameworks of Delaware and Maryland are similar

In this assessment, arsenic never exceeded the PMCL, but it was detected in 24 (13%) of 192 analyses (Figure 22). Detections ranged from 0.0004 mg/L to 0.009 mg/L, just below the 0.01 mg/L PMCL. Aquifer type was established for 67 (35%) of the 192 analyses. Of these 67 analyses, 12 were associated with unconfined wells, 3 were associated with semi-confined wells, and 52 were associated with confined wells. Arsenic was not detected in the 12 unconfined well analyses; 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. Arsenic was detected in 10 confined wells and 1 semi-confined well; most (7 out of 11) of these wells are situated in southernmost New Castle County and Kent County (Figure 23b). The majority of these wells (9 total) are screened in geologic formations mapped as glauconitic and (or) marine deposits (Ramsey, 2005, 2007). The two remaining wells with arsenic detections are located in the northernmost portion of the Coastal Plain and screened in the Potomac Formation, which is primarily a fluvial deposit (McKenna et al., 2004; Figure 23b).

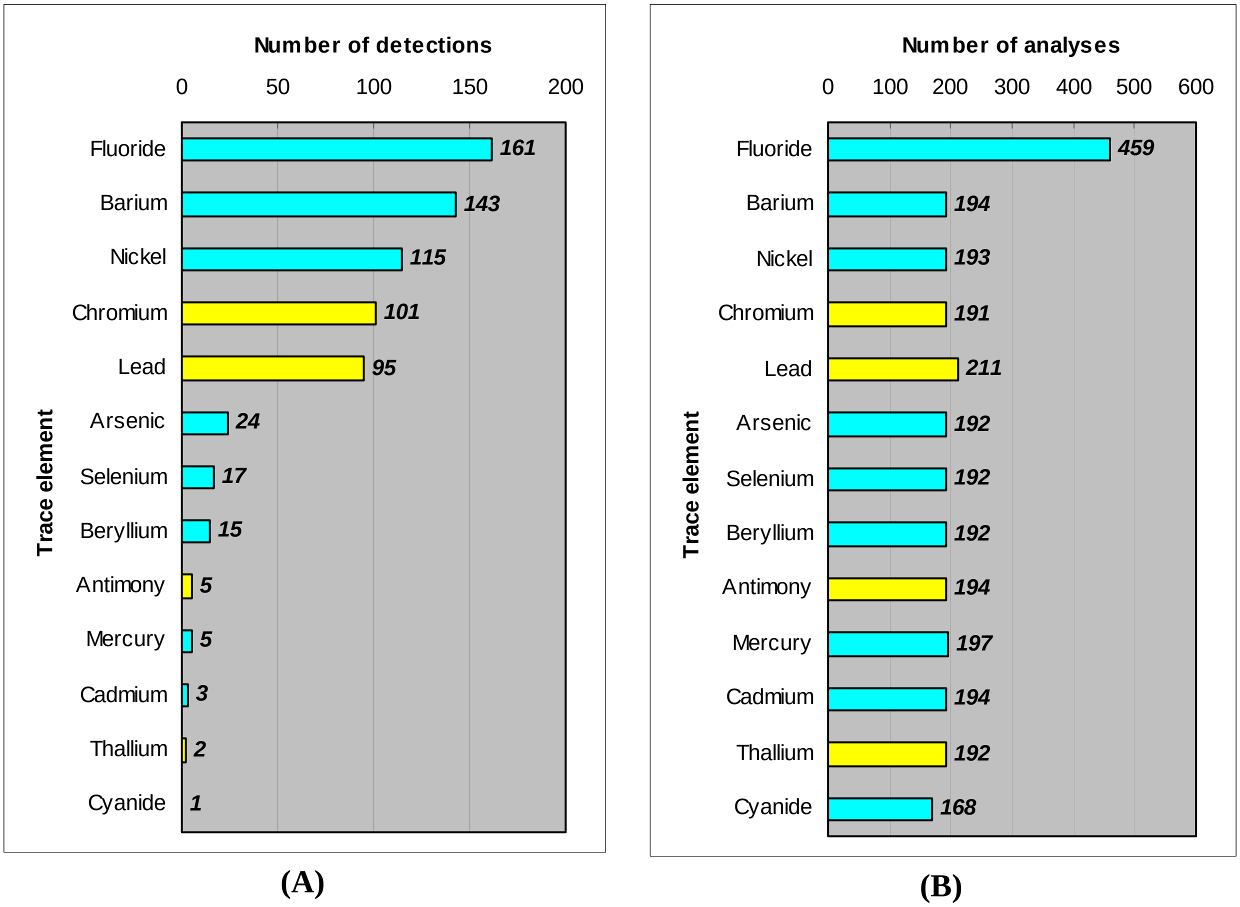


Figure 22. Frequency distributions of trace element detections (A) and analyses (B). [Bars highlighted yellow indicate one or more concentration above the PMCL.]

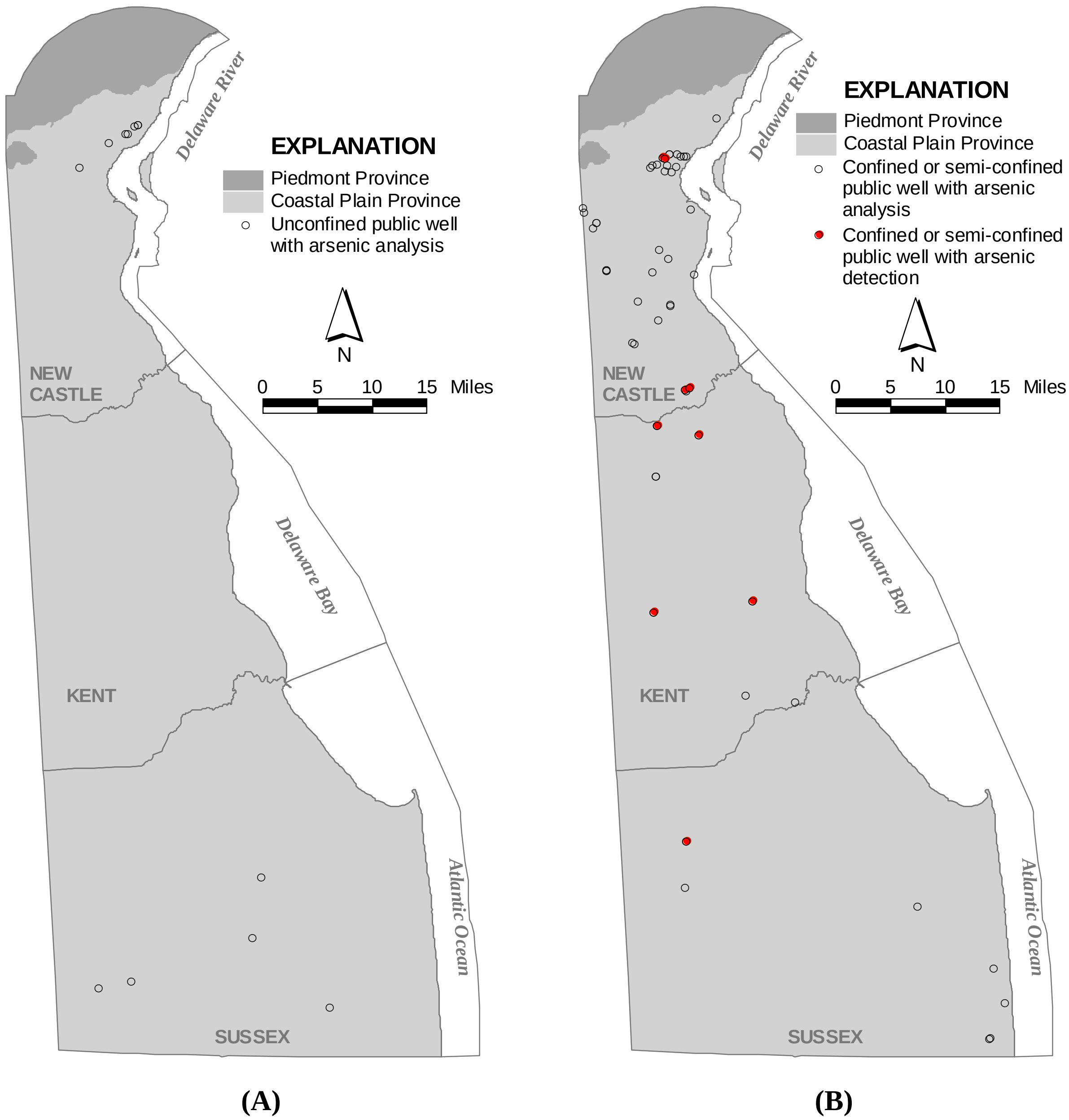


Figure 23. Maps showing arsenic analyses and detections in unconfined (A) and confined and semi-confined (B) public water-supply wells.

Radionuclides

Radionuclide data are limited to 82 analyses and summarized as follows: uranium-238 (48 analyses), radium-226 and radium-228 combined (2 analyses), and gross alpha particle activity (32 analyses). The PMCLs for these parameters are 0.03 mg/L, 5 pCi/L, and 15 pCi/L (DHSS, 2005; U.S. EPA, 2006). None of the concentrations or activities exceeded the PMCL. For more information on radionuclides in Delaware ground water, 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 ground-water quality in Delaware based on data collected during 2006-07 from public water-supply wells. The results of this assessment serve as "Part IV: Ground-Water Assessment" of Delaware's overall 2008 305(b) report (DNREC, 2008). 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 (65,182 analyses) indicative of raw or apparently raw ground-water 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, 2006; 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. (Although the karst aquifer is recognized in this assessment, no analytical data could be established for this aquifer type.) As of April 2008, there were 1,000 active public water-supply wells in Delaware. Most of the wells (86%) produce from Coastal-Plain aquifers while a much smaller percentage of the wells (7%) produce from Piedmont aquifers. Aquifer type could not be established for the remaining 8% of the wells. Overall, well depths range from 22 to 957 ft below land surface (bls) with a median well depth of 136 ft bls.

Ground water in the unconfined and fractured-rock aquifers is predominantly soft and acidic. Specifically, hardness as $CaCO_3$ was less than 60 mg/L in 75 and 89% of the samples, respectively, and pH values were less than the lower limit of the Secondary Maximum Contaminant Level or SMCL range (6.5 to 8.5 S.U.) in 97 and 89% of the samples, respectively. In contrast, ground water in the confined and semi-confined aquifers is predominantly moderately hard or harder with more neutral pH. Specifically, hardness as $CaCO_3$ was greater than 61 mg/L in 66 and 80% of the samples, respectively, and pH values were within the SMCL range in 59 and 71% of the samples, respectively. Overall, iron exceeded the 0.3 mg/L SMCL in a considerable fraction of the samples (35%) and was found above the SMCL in all aquifer types and at virtually all depths. Semi-confined and confined aquifers, however, had the highest median iron concentrations (0.25 and 0.12 mg/L) and the largest percentage of concentrations greater than the SMCL (50 and 40%, respectively). Total dissolved solids (TDS) and chloride concentrations exceeded the SMCLs (500 and 250 mg/L, respectively) in very small fractions of the samples (1 and 2%, respectively). All of the TDS and chloride SMCL exceedences were associated with confined wells. Overall, sodium concentrations exceeded the Health Advisory or HA (20 mg/L) in a considerable fraction of the samples (30%). Sodium was detected above the HA in all aquifer types, but confined wells had the largest percentage of concentrations (34%) above the HA. Moreover, most of the sodium concentrations above 100 mg/L were associated confined wells screened in glauconitic aquifers where elevated concentrations have been attributed to ion-exchange processes (Spoljaric, 1986).

Of the aquifer types evaluated, the unconfined aquifer is the most susceptible to human impacts. Using nitrate as a proxy to indicate the extent of human influence on ground-water quality, this aquifer had the most elevated nitrate concentration (21.5 mg/L), the highest median nitrate concentration (4.70 mg/L), the largest percentage of concentrations greater than 0.4 mg/L (88%), and the largest percentage of concentrations above the 10 mg/L Primary Maximum Contaminant Level or PMCL (10%). Fractured-rock aquifers had the second-highest median nitrate concentration (2.70 mg/L) and the second-largest percentage of concentrations greater than 0.4 mg/L (78%). Confined and semi-confined aquifers, in contrast, had lower median nitrate concentrations (zero mg/L or non-detectable) and smaller percentages of the concentrations exceeded 0.4 mg/L (26 and 25%, respectively). Nonetheless, the data indicate that these aquifer types are equally susceptible to human influence. Moreover, nitrate concentrations exceeded the PMCL in 3 (4%) of the confined well analyses, suggesting either poor confinement or compromised well construction. Regardless of aquifer type, the vertical extent of human influence was limited to depths of 225 ft below land surface (bls) and shallower; at greater depths nitrate was rarely detected above the quantitation limit. Laterally, 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 10,875 analyses. When detected, OCs were reported at concentrations less than 1 μg/L in about half (52%) of the detections or about 1% of the analyses. Several disinfection byproducts, such as chloroform and dichloromethane, are among the top-ten most-frequently detected OCs. PMCLs were exceeded in a very small fraction (11 or 0.1%) of the analyses. Most of the PMCL exceedences that could be linked by aquifer type were associated with unconfined wells. Methy tert-butyl ether (MTBE), trichloroethylene (TCE), and tetrachloroethylene (PCE) were among the top-ten most-frequently detected OCs, consistent with Ferrari (2001), and each had 3 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 ~200 ft bls and shallower; at greater depths these contaminants were not detected. As previously noted, similar trends in nitrate with respect to sample depth were identified. More than half (59%) of the active public water-supply wells are less than 200-ft deep (Figure 3). The cause for these trends cannot be explained based on available data. However, one or more of the following reasons appear plausible: (1) there is sufficient confinement at depths greater than 200 ft bls or (2) insufficient time has passed for contaminants to reach deeper aquifer systems.

Similar to OCs, trace elements were not frequently detected and rarely exceeded PMCLs when detected. Specifically, trace elements were not detected in 75% of 2,769 analyses. When detected, trace elements were reported at concentrations less than 0.1 mg/L in almost three quarters (72%) of the detections or about 18% of the analyses. Barium was the most-frequently detected trace element. PMCLs or action levels were exceeded in a very small fraction (15 or 0.5%) of the analyses, most of which (11) were lead exceedences. An analysis of arsenic data suggests that that this element is primarily limited to confined or semi-confined aquifers occurring in geologic formations mapped as glauconitic or marine deposits.

This 305(b) ground-water-quality assessment is DNREC's first attempt to report ambient 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) ground-water-quality assessments should provide a more complete picture of ground-water quality in Delaware.

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