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

Delaware's 2012 305(b) Groundwater-Quality Assessment Based on Public-Well Data: Results of Sampling, 2010-11

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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, 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 primarily on the quality of navigable [surface] waters, Section 106(e) 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 and 2010 305(b) groundwater-quality assessments (Kasper, 2008, 2010).

Purpose and scope

This report serves as "Part IV: Groundwater Assessment" of Delaware's overall 2012 305(b) report (DNREC, 2012). 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 2010 and 2011. 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. Douglas Rambo of the DNREC assisted with the acquisition of SWAPP data. John T. Barndt, P.G. of the 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.

Table 1. Hydrostratigraphic units in Delaware. [Modified after the Delaware Geological Survey, http://www.dgs.udel.edu/delaware-geology/hydrologic-stratigraphic-chart, accessed March 19, 2012.]

AGE	GEOLOGIC UNITS	HYDROLOGIC UNITS
Holocene	various informal deposits	Unassigned
Pleistocene	Delaware Bay Group	Columbia aquifer
	Nanticoke River Group	
	Assawoman Bay Group	
	unassigned	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 beds
		Frederica aquifer
		Confining beds
		Federalsburg aquifer
		Confining beds
		Cheswold aquifer
		Confining beds
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 beds
	Englishtown Fm.	Englishtown aquifer
	Merchantville Fm.	Confining beds
	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

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 (2010-11). Data resulting from these queries (50,705 analyses) were provided to DNREC in a February 17, 2012 Microsoft Office Access 2007 ("Access") database. Records obtained from the SWAPP database were current as of February 20, 2012. 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, 2011). 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 75th and 25th percentiles)
QL is the lower quartile or 25th percentile (i.e, the bottom of the box in Figure 4)
QU is the upper quartile or 75th 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.

Public wells

As of February 20, 2102, there were 1,158 active public water-supply wells in the SWAPP database. Of the active wells, 1,137 (98%) have geographic coordinates and are plotted in Figure 1A. With reference to Figure 1A, there are 244 wells (21%) in New Castle County, 301 wells (26%) in Kent County, and 592 wells (52%) in Sussex County. (Percentages in this report may not total 100% due to rounding.)

Aquifer type is known for 948 (82%) of the 1,158 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 887 (77%) and Piedmont wells account for 61 (5%) (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 210 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 1,158 active wells, unconfined wells account for 409 (35%), confined wells account for 428 (37%), and semi-confined wells account for 50 (4%) (Figure 2). A large majority of the unconfined wells with geographic coordinates (329 of 409 or 80%) are located in Sussex County; the remaining unconfined wells include 47 (11%) in Kent County and 33 (8%) in New Castle County (Figure 1B). Confined wells are more evenly distributed throughout the Coastal Plain of Delaware, with most of these wells situated in Kent County (Figure 1C). Specifically, out of 426 confined wells with geographic coordinates, 174 (41%) are located in Kent County, 130 (31%) are located in New Castle County, and 122 (29%) are located in Sussex County. All 50 semi-confined wells have geographic coordinates (Figure 1D); 26 (52%) are located in Kent County, 18 (36%) are located in Sussex County, and 6 (12%) 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 1,158 active wells, fractured-rock wells account for 50 (4%) and karst wells account for 11 (1%) (Figure 2). All 50 fractured-rock and 11 karst wells (Figure 2) have geographic coordinates and are plotted in Figures 1E and 1F, respectively. Karst wells coincide 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 1,049 (91%) of 1,158 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 138 ft bls and the 25^{th} and 75^{th} percentiles are 88 and 240 ft bls, respectively. Well depths are not known for 109 (9%) of the active wells (Figure 3).

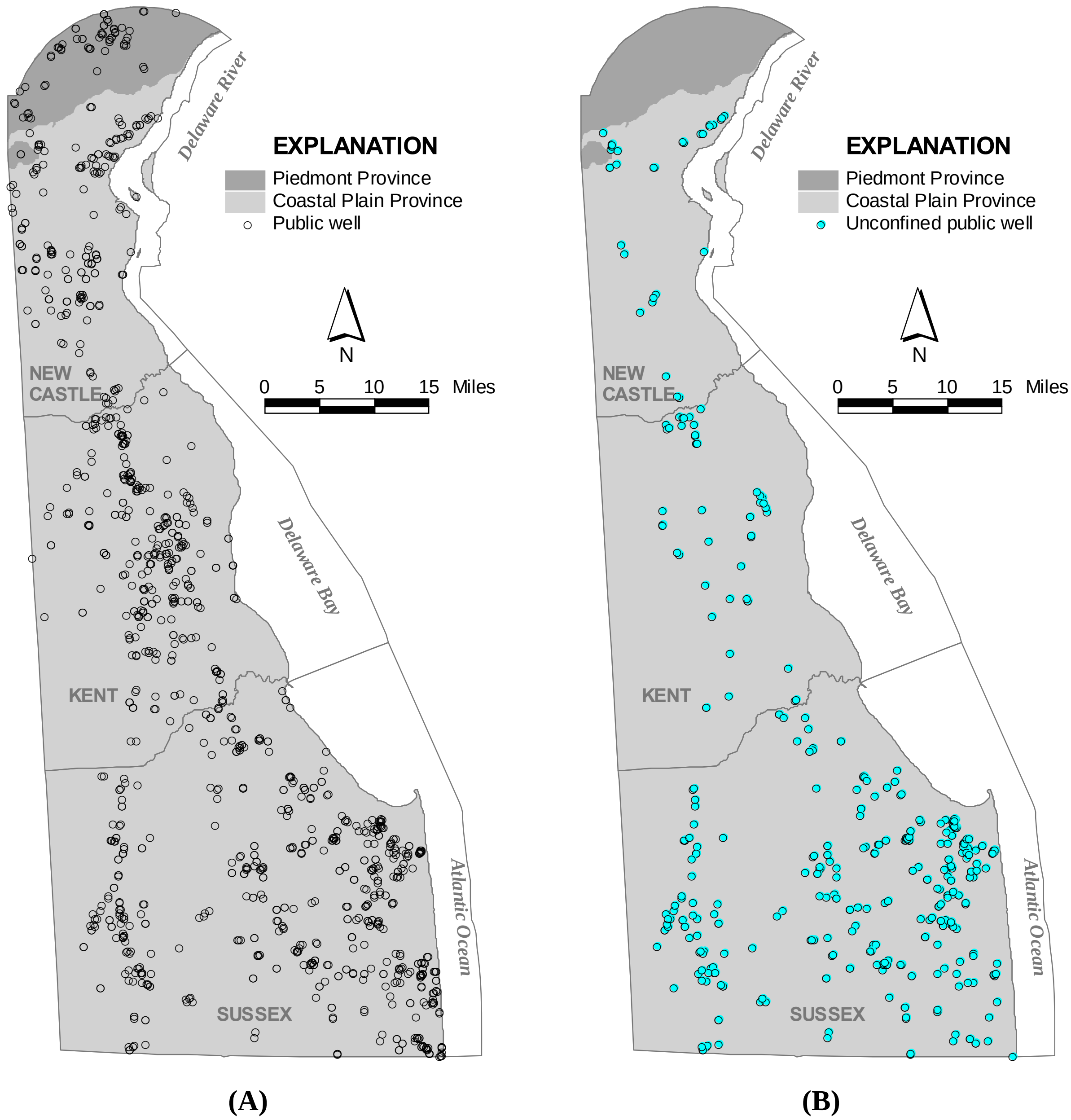
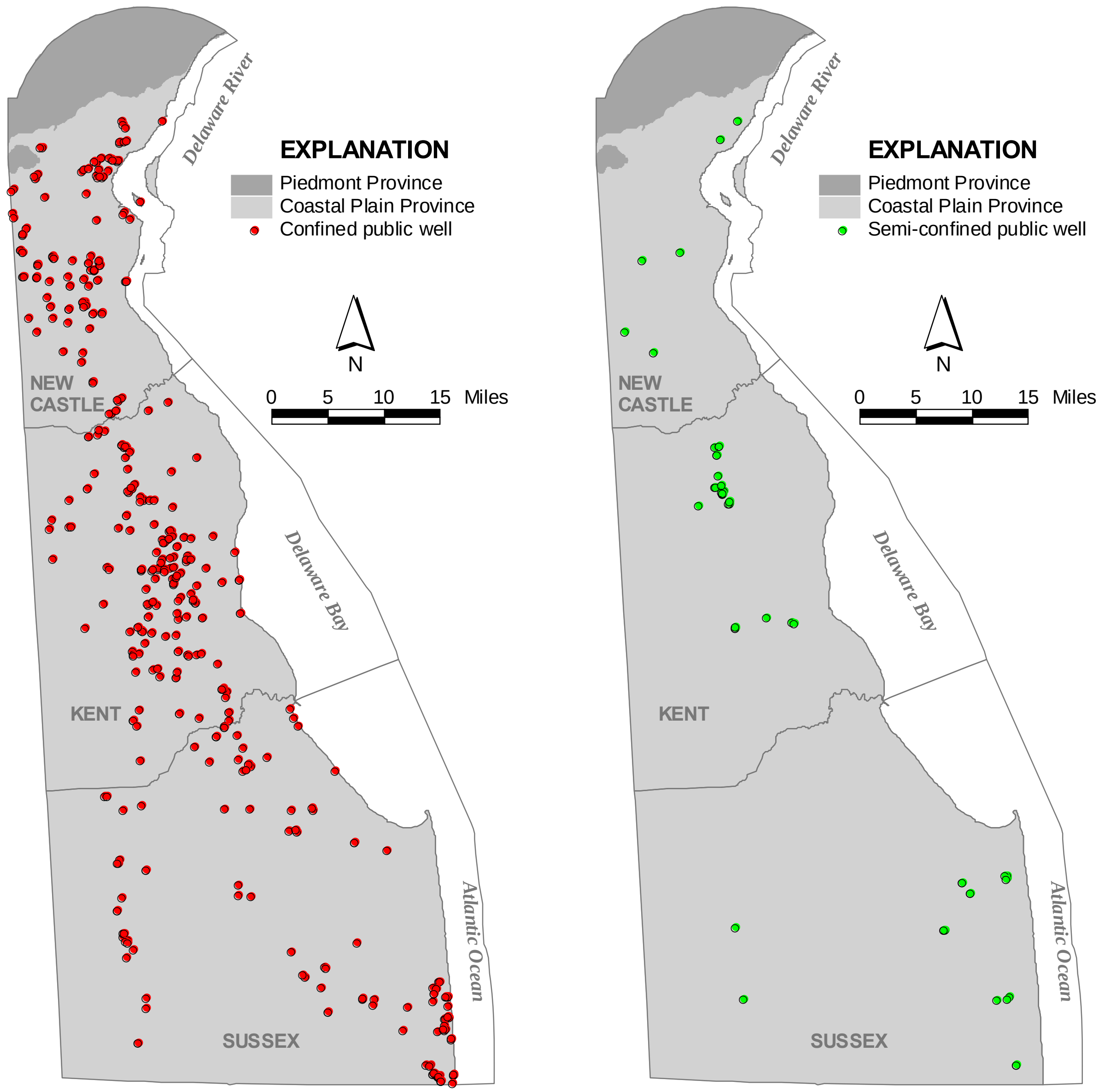


Figure 1. Maps of active public water-supply wells in Delaware – (A) all wells and (B) unconfined wells.



(C) **(D)**

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

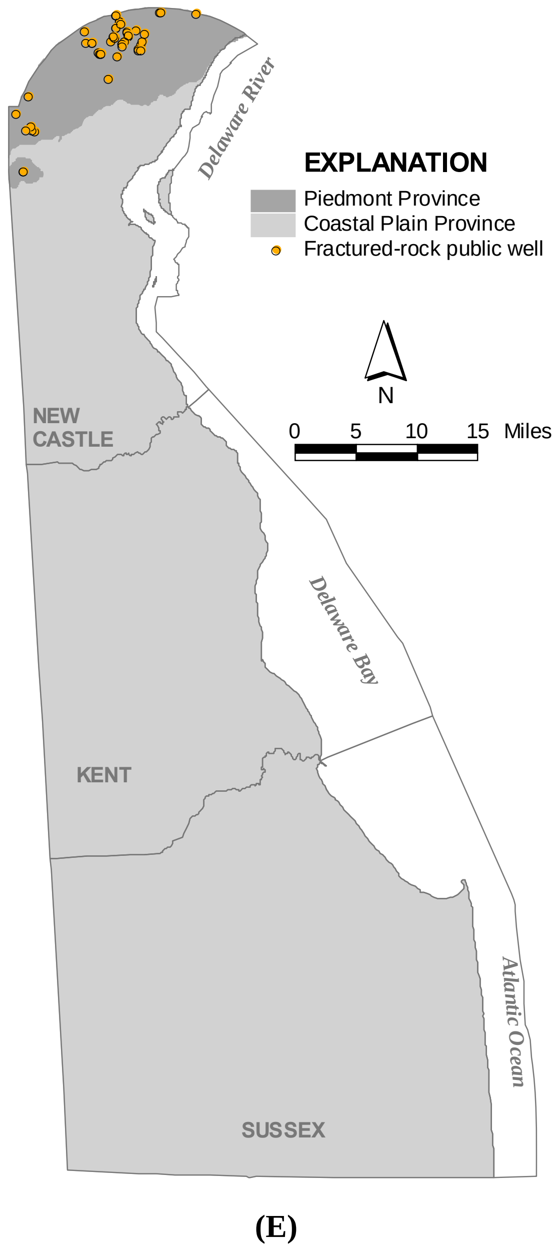


Figure 1. Maps of active public water-supply wells in Delaware (*cont.*) – (E) fractured-rock wells and (F) karst wells.

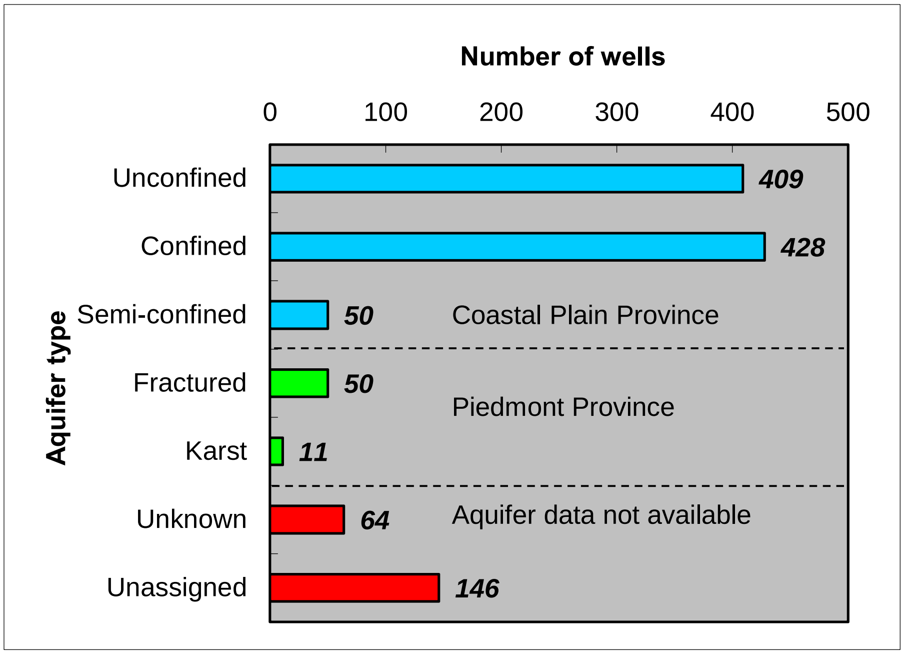


Figure 2. Histogram of active public water-supply wells by aquifer type.

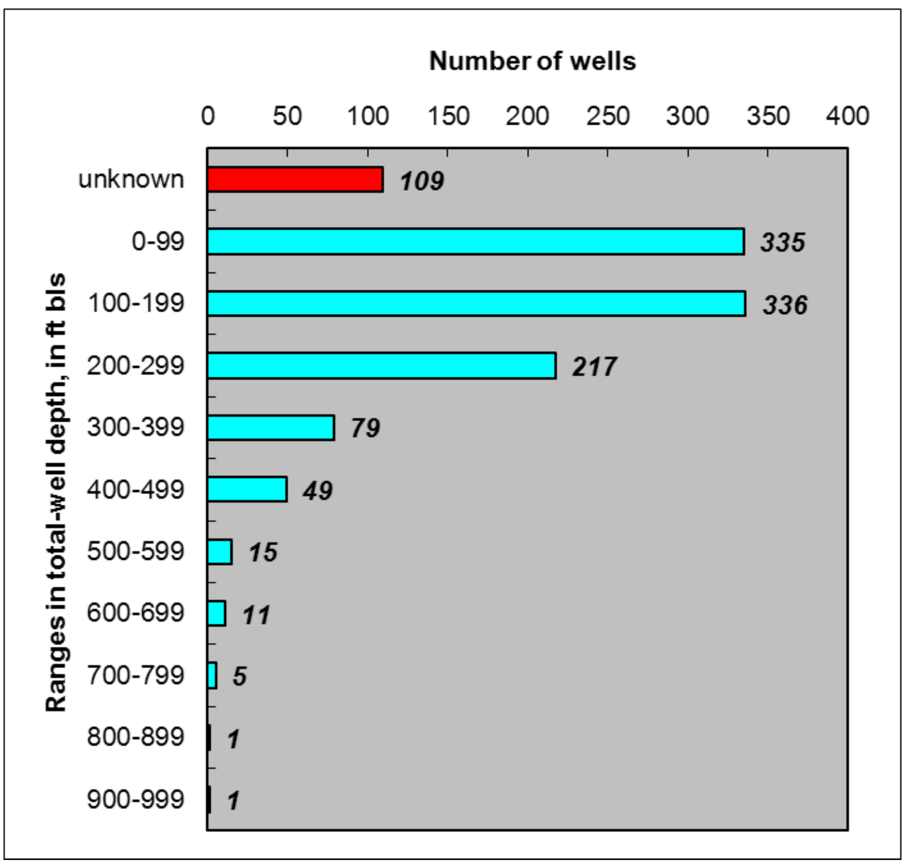


Figure 3. Histogram of active public water-supply wells by ranges in total-well depth.

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, 2011). 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, 1,270 nitrate as nitrogen ("nitrate") analyses are in the SDWIS query provided to DNREC. Of these, 251(20%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 195 nitrate analyses where aquifer type is known (Table 2). This number translates to ~21% of the total number of wells (948) where aquifer type is known (Figure 2). Overall, nitrate concentrations ranged from nondetectable to 27.5 mg/L with a median value of 1.20 mg/L (Table 2 and Figure 4). Nitrate was not detected above the laboratory quantitation limit in 85 (44%) of the 195 analyses (Table 2). Concentrations in 107 (55%) 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 10 (5%) of the 195 samples (Table 2). All but one of the PMCL exceedences occurred in Sussex County; the remaining exceedence occurred in New Castle County (Figure 5). Overall, nitrate concentrations decrease with depth and, below depths of ~100 ft bls, concentrations never exceeded 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 86 (44%) of the 195 individual samples linked by DNREC ID (Table 2). This number translates to ~21% of the total number of active unconfined wells (409) statewide (Figure 2). Nitrate was not detected above the laboratory quantitation limit in 8 (9%) of the 86 samples. Concentrations in 77 (90%) of the 86 samples exceeded 0.4 mg/L suggesting that groundwater quality in the unconfined aquifer is largely affected by human activities. Nitrate concentrations below 0.4 mg/L may reflect natural groundwater quality or geochemical conditions that do not favor nitrification. For example, the cluster of concentrations below 0.4 mg/L in southeastern Sussex County coincides with an area where groundwater is largely anoxic (Figure 5a; Kasper and Strohmeier, 2007). The most elevated nitrate concentration (27.5 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 second-lowest percentage of nondetects (Table 2). The median nitrate concentration is in agreement with the median concentration (4.884 mg/L) from a recent USGS study of 30 randomly-selected unconfined public water-supply wells in Delaware (Reyes, 2010). Moreover, the median nitrate concentration from this study is slightly 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 10 (12%) of the 86 unconfined aquifer samples (Table 2). Of these, 9 occurred in Sussex County and 1 occurred in New Castle County (Figure 5a). This percentage of PMCL exceedences is higher than the percentage reported by Reyes (2010), who found two out of 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 (27.5 mg/L) was detected at a depth of 80 ft bls. The deepest PMCL exceedence (11.9 mg/L) occurred at a depth of 100 ft bls and the shallowest PMCL exceedence (12.95 mg/L) occurred at a depth of 59 ft bls. At depths shallower than 59 ft bls, nitrate concentrations were ~5 mg/L or less based on data for 12 unconfined wells.

Confined wells account for 91 (47%) of the 195 individual samples linked by DNREC ID (Table 2). This number translates to ~21% of the total number of active confined wells (428) statewide (Figure 2). Nitrate was not detected above the laboratory quantitation limit in 71 (78%) of the 91 samples. However, concentrations in 18 (20%) of the 91 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 (Table 2). Of these, 15 are confined Potomac aquifer wells located in the northernmost portion of the Coastal Plain in New Castle County (Figure 5b). Nitrate concentrations in confined wells never exceeded the PMCL (Table 2; Figure 5b). Nitrate concentrations generally decrease with depth in confined aquifers, consistent with the overall trend (Figure 6).

Semi-confined wells account for 6 (3%) of the 195 individual samples linked by DNREC ID (Table 2). This number translates to ~12% of the total number of active semi-confined wells (50) statewide (Figure 2). Nitrate was not detected above the laboratory quantitation limit in 3 (50%) of the 6 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 (50%) exceeded 0.4 mg/L, indicating the potential for human influence on groundwater quality. Nitrate concentrations in semi-confined wells never exceeded the PMCL (Table 2; Figure 5b).

Fractured-rock wells account for 4 (~2%) of the 195 individual samples linked by DNREC ID (Table 2). This number translates to ~8% of the total number of fractured-rock wells (50) statewide (Figure 2). Although data are extremely limited, nitrate concentrations in 1 of the 4 fractured-rock wells exceeded 0.4 mg/L. None of the nitrate concentrations in fractured-rock wells exceeded the PMCL.

Karst wells account for 8 (~4%) of the 195 individual samples linked by DNREC ID (Table 2). This number translates to ~89% 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 (3.38 mg/L; Table 2), but none of the concentrations exceeded the PMCL. There is no discernible trend in nitrate versus depth for karst wells based on available data; however, most of the deepest nitrate detections are associated with karst wells (Figure 6).

Table 2. Statistical summary of nitrate data by aquifer type. [mg/L, milligrams per liter; ND, not detected above laboratory quantitation limit; PMCL, primary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2011).]

Statistics	All Wells	Unconfined Wells	Confined Wells	Semi-Confined Wells	Fractured-Rock Wells	Karst Wells
Number of wells/samples (#)	195	86	91	6	4	8
Percent of total (%)	100	44	47	3	2	4
Maximum (mg/L)	27.50	27.50	7.90	5.93	1.90	5.03
75th percentile (mg/L)	4.98	7.02	ND	3.64	0.48	4.22
50th percentile (mg/L)	1.20	4.70	ND	1.77	ND	3.38
25th percentile (mg/L)	ND	2.10	ND	ND	ND	2.30
Minimum (mg/L)	ND	ND	ND	ND	ND	2.11
Number not detected (#ND)	85	8	71	3	3	0
Percent not detected (%ND)	44	9	78	50	75	0
Number > 0.4 mg/L (#)	107	77	18	3	1	8
Percent > 0.4 mg/L (%)	55	90	20	50	25	100
Number > 10 mg/L PMCL (#)	10	10	0	0	0	0
Percent > 10 mg/L PMCL (%)	5	12	0	0	0	0

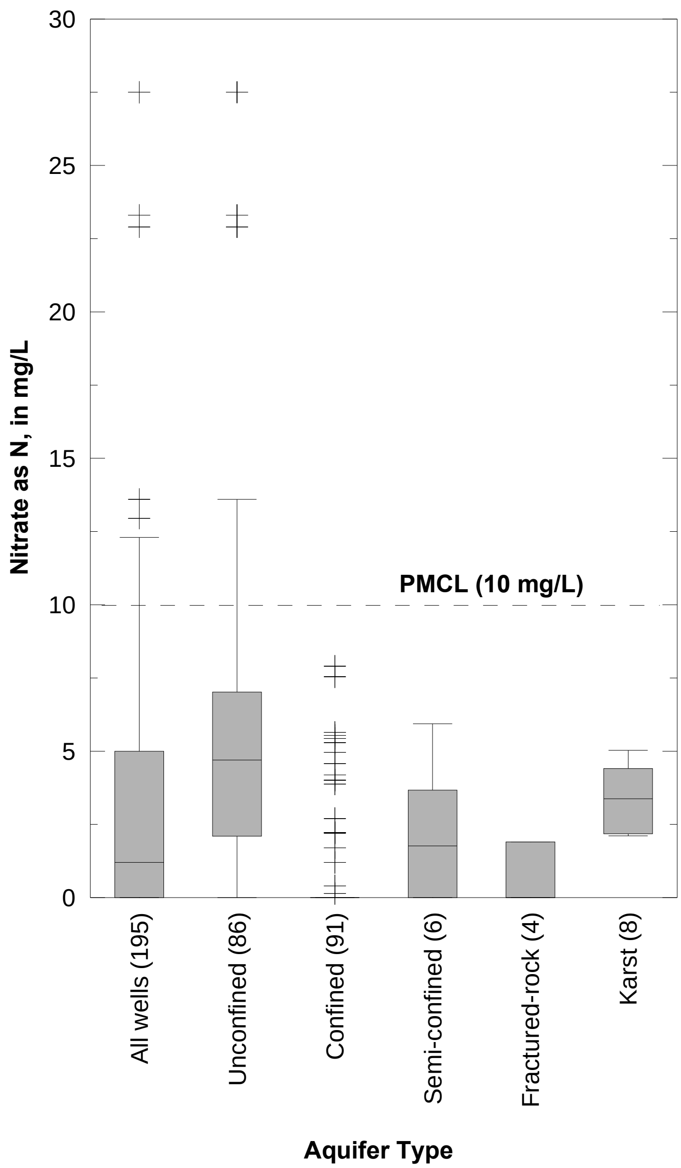


Figure 4. Percentile diagrams of nitrate data by aquifer type. [mg/L, milligrams per liter; crosses, outliers; (#), number of samples per aquifer type; PMCL, primary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2011).]

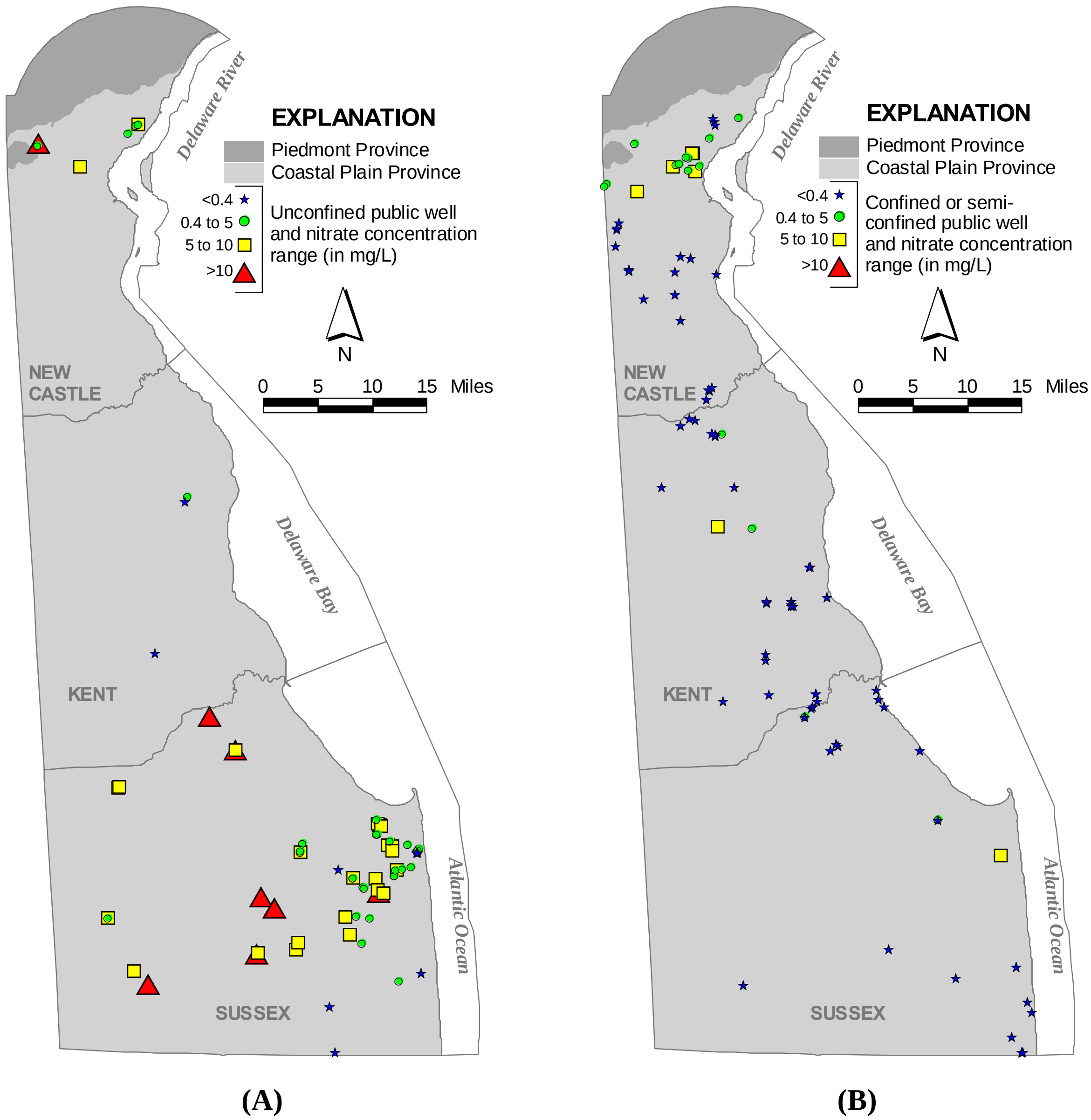


Figure 5. Maps showing nitrate concentration ranges in (A) unconfined and (B) confined and semi-confined public water-supply wells.

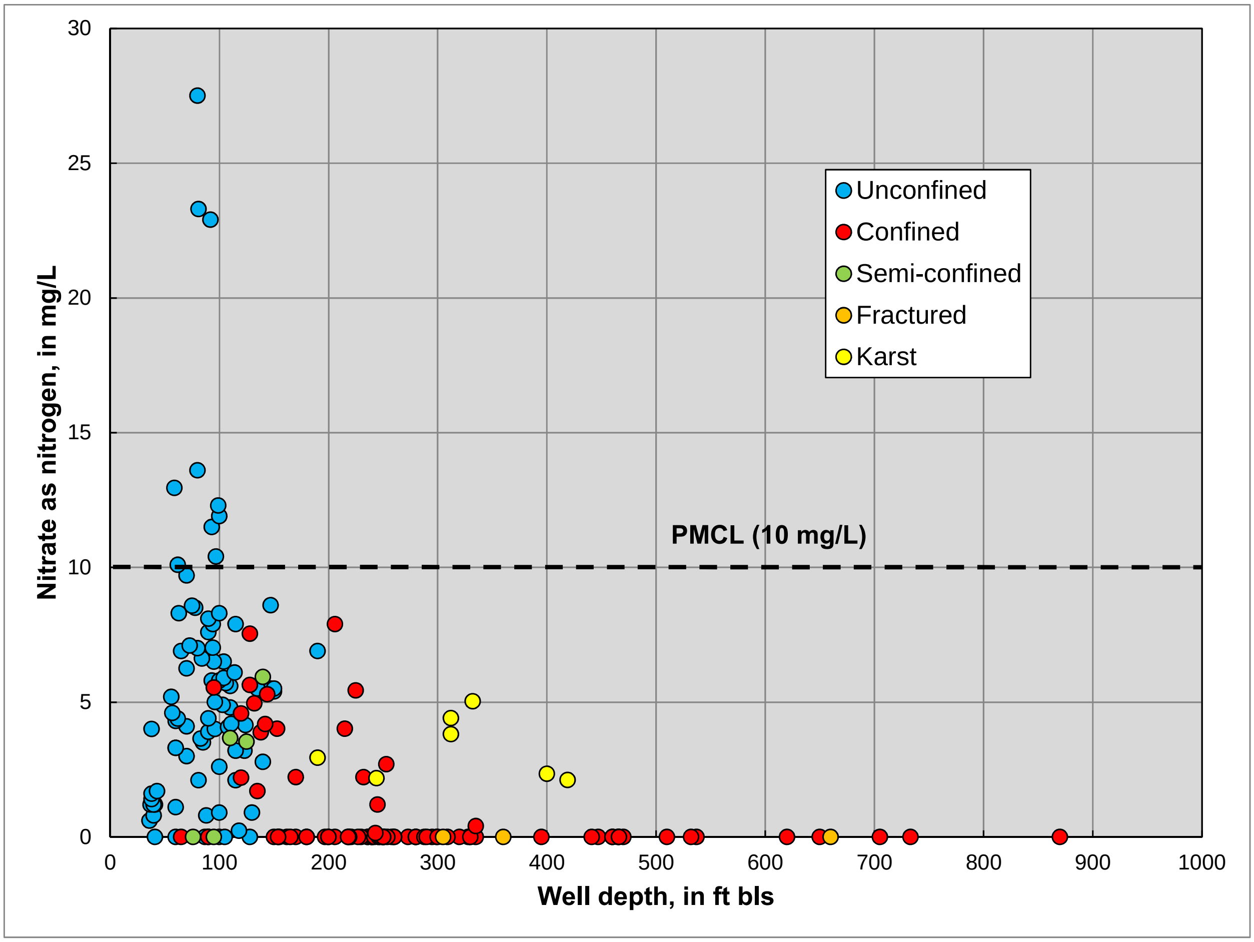


Figure 6. Scatter plot of nitrate versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface; PMCL, primary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2011).]

Total dissolved solids

Overall, 432 total dissolved solids (TDS) analyses are in the SDWIS query provided to DNREC. Of these, 195 (51%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 166 TDS analyses where aquifer type is known (Table 3). This number translates to ~18% of the total number of wells (948) where aquifer type is known (Figure 2). Overall, TDS concentrations ranged from 24 to 788 mg/L with a median value of 156 mg/L (Table 3 and Figure 7). TDS concentrations exceeded the SMCL (500 mg/L) in 4 (2%) of the 166 analyses (Table 3).

Although data are limited, karst wells had the highest median TDS concentration (403 mg/L) and concentrations exceeded the SMCL in 2 (25%) of the 8 analyses (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 74 samples, unconfined wells had the lowest median TDS concentration (130 mg/L; Table 3 and Figure 7), a value that agrees in general with the median value of 116 mg/L reported by Ferrari (2001) and Reyes (2010). The median TDS concentrations for confined and semi-confined wells (186 and 176 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. TDS concentrations in confined wells exceeded the SMCL in 2 (3%) of the 77 analyses (Table 3). TDS concentrations generally increase with depth; however, there are several wells that deviate from the general trend and they are all screened in the Potomac aquifer (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, 2011).]

Statistics	All Wells	Unconfined Wells	Confined Wells	Semi-Confined Wells	Fractured-Rock Wells	Karst Wells
Number of wells/samples (#)	166	74	77	5	2	8
Percent of total (%)	100	45	46	3	1	5
Maximum (mg/L)	788	384	788	254	242	571
75th percentile (mg/L)	215	158	234	200	215	459
50th percentile (mg/L)	156	130	186	176	187	403
25th percentile (mg/L)	107	99	133	170	160	321
Minimum (mg/L)	24	24	42	155	132	235
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 (#)	4	0	2	0	0	2
Percent > 500 mg/L SMCL (%)	2	0	3	0	0	25

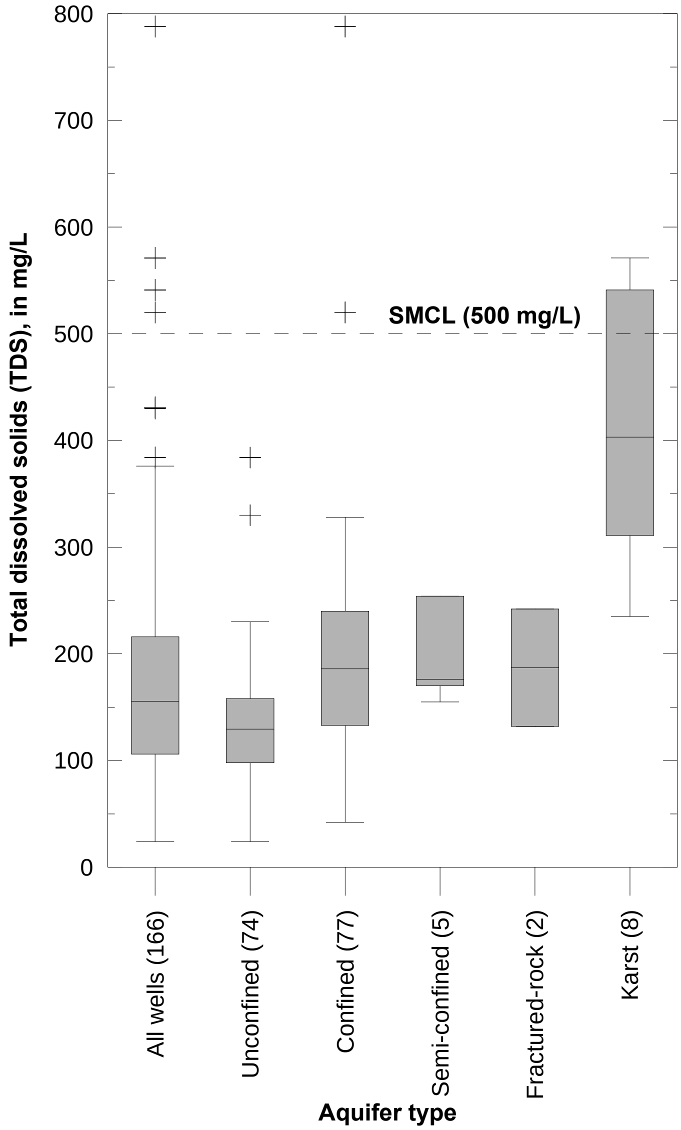


Figure 7. Percentile diagrams of total dissolved solids (TDS) data by aquifer type. [mg/L, milligrams per liter; crosses, outliers; (#), number of samples; SMCL, secondary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2011).]

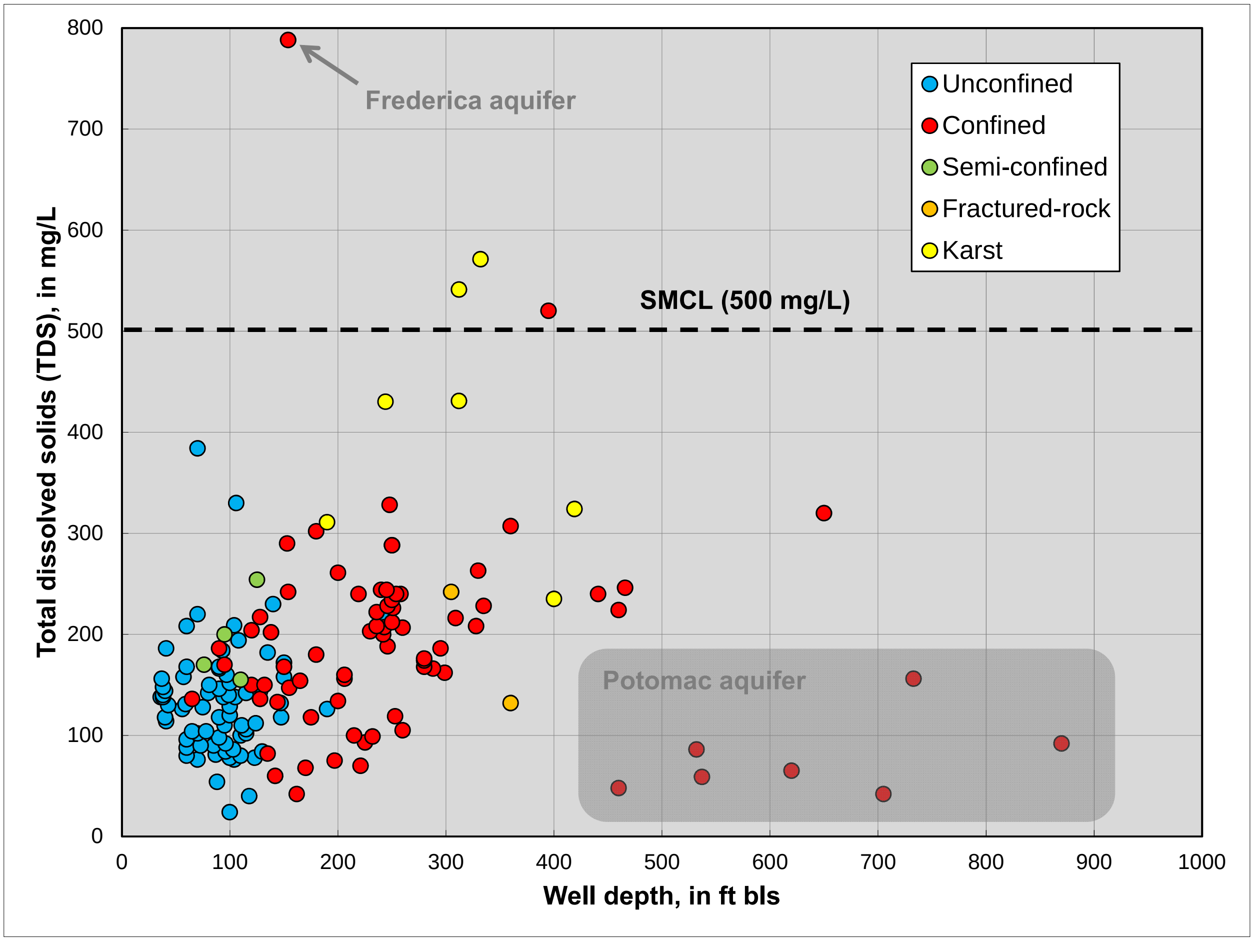


Figure 8. Scatter plot of total dissolved solids (TDS) versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface; SMCL, secondary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2011).]

Chloride

Overall, 1060 chloride analyses are in the SDWIS query provided to DNREC. Of these, 252 (24%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 194 chloride analyses where aquifer type is known (Table 4). This number translates to ~20% of the total number of wells (948) where aquifer type is known (Figure 2). Overall, chloride concentrations ranged from ND to 177 mg/L with a median value of 15.2 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 (48.3 mg/L; Table 4 and Figure 9), consistent with the TDS results discussed previously. The most elevated chloride concentration, however, was associated with an unconfined well. Unconfined and fractured-rock wells had the second- and third-highest median chloride concentrations (17.0 and 13.0 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 of 18.3 mg/L and Reyes' (2010) median of 18.6 mg/L. Semi-confined and confined wells had the lowest median chloride concentrations (12.2 and 3.9 mg/L, respectively), although data for semi-confined wells are limited. Overall, there is a decreasing trend in chloride concentrations with depth (Figure 10).

Table 4. Statistical summary of chloride data by aquifer type. [mg/L, milligrams per liter; ND, not detected above laboratory quantitation limit; SMCL, secondary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2011).]

Statistics	All Wells	Unconfined Wells	Confined Wells	Semi-Confined Wells	Fractured-Rock Wells	Karst Wells
Number of wells/samples (#)	194	79	97	6	4	8
Percent of total (%)	100	41	50	3	2	4
Maximum (mg/L)	177.0	177.0	113.0	82.4	89.9	62.6
75th percentile (mg/L)	26.1	29.0	20.9	21.5	33.1	54.2
50th percentile (mg/L)	15.2	17.0	3.9	12.2	13.0	48.3
25th percentile (mg/L)	3.7	14.3	1.7	3.7	10.3	37.3
Minimum (mg/L)	ND	5.6	ND	3.0	5.9	15.6
Number not detected (#ND)	1	0	1	0	0	0
Percent not detected (%ND)	1	0	1	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

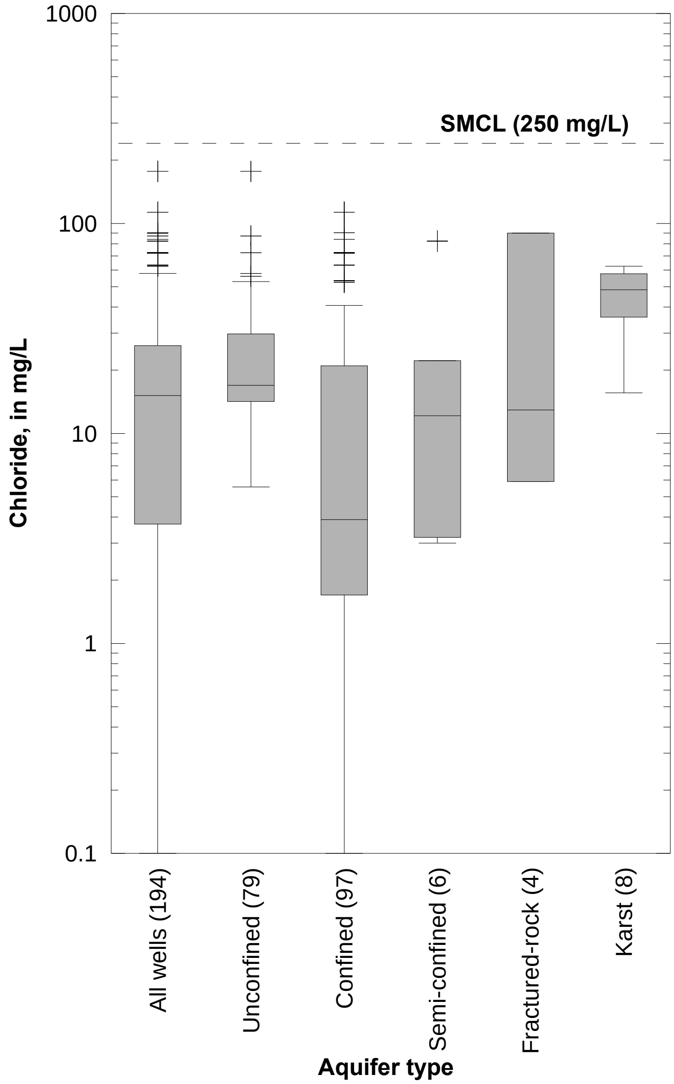


Figure 9. Percentile diagrams of chloride data by aquifer type. [mg/L, milligrams per liter; crosses, outliers; (#), number of samples; SMCL, secondary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2011).]

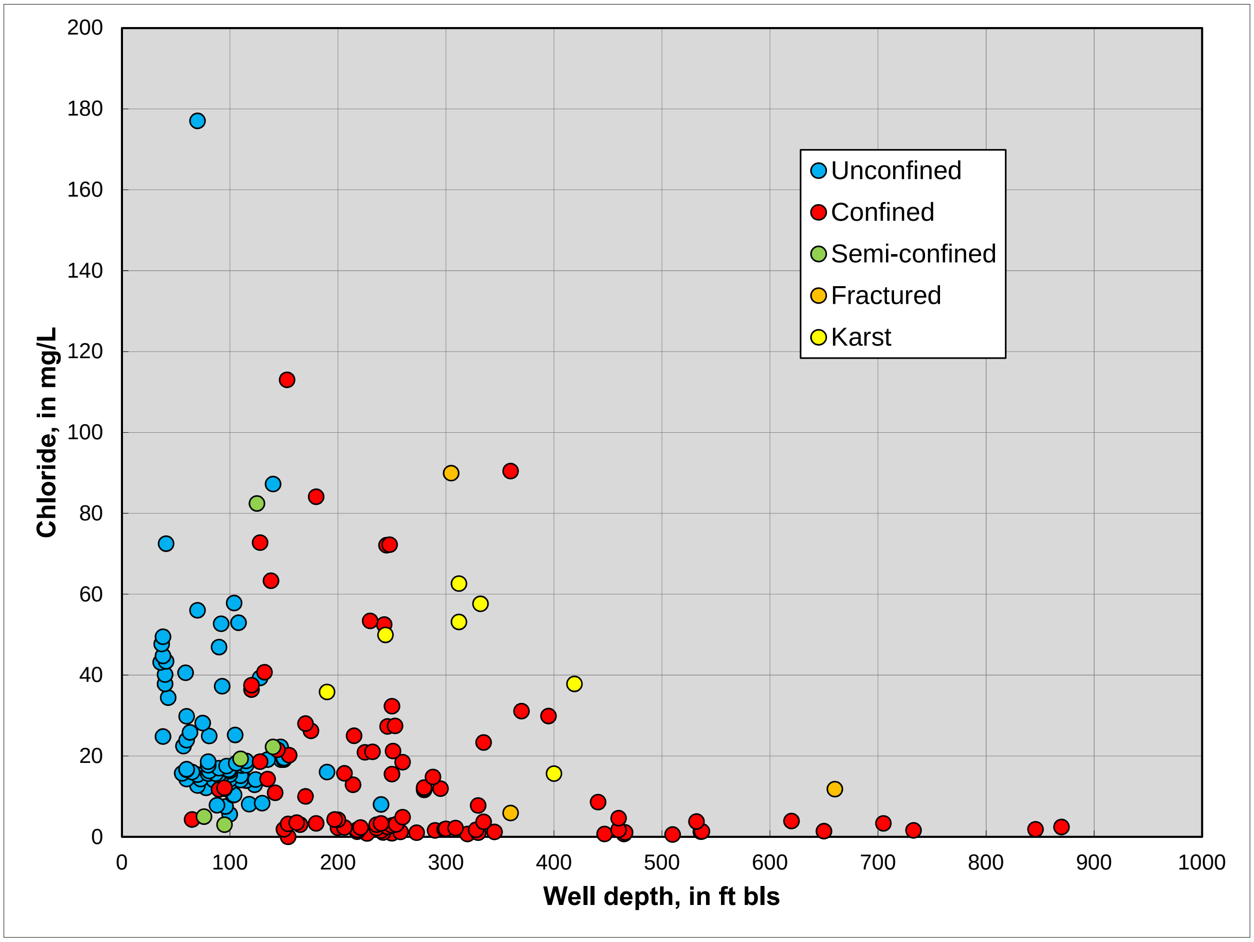


Figure 10. Scatter plot of chloride versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface.]

Sodium

Overall, 716 sodium analyses are in the SDWIS query provided to DNREC. Of these, 217 (30%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 179 sodium analyses where aquifer type is known (Table 5). This number translates to ~19% of the total number of wells (948) where aquifer type is known (Figure 2). Overall, sodium concentrations ranged from 3.1 to 209 mg/L with a median value of 11.7 mg/L (Table 5 and Figure 11). Sodium concentrations exceeded the HA (20 mg/L) in 49 (27%) of the 179 samples (Table 5).

Unconfined and fractured-rock wells had the highest median sodium concentrations (12.5 and 12.9 mg/L, respectively; Table 5 and Figure 11), although data for fractured-rock wells are very limited. The median value for the unconfined aquifer is within the range of Ferrari's (2001) median of 11.7 mg/L and Reyes' (2010) median of 14.2 mg/L. Unconfined wells also had a large fraction of concentrations above the HA (23%; 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 wells had a relatively lower median sodium concentration (11.0 mg/L). Confined wells, however, had the highest sodium concentrations overall (up to 209 mg/L) and the largest fraction of concentrations above the HA (34%; 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). Semi-confined and karst wells had the lowest median sodium concentrations (6.4 and 8.8 mg/L, respectively; Table 5 and Figure 11) and concentrations never exceeded the HA in karst 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; ND, not detected above laboratory quantitation limit; HA, health advisory for public water-supply systems (U.S. EPA, 2011).]

Statistics	All Wells	Unconfined Wells	Confined Wells	Semi-Confined Wells	Fractured-Rock Wells	Karst Wells
Number of wells/samples (#)	179	74	88	5	4	8
Percent of total (%)	100	41	49	3	2	4
Maximum (mg/L)	209.0	95.6	209.0	42.1	35.7	19.8
75th percentile (mg/L)	20.8	17.9	30.3	7.9	20.6	14.8
50th percentile (mg/L)	11.7	12.5	11.0	6.4	12.9	8.8
25th percentile (mg/L)	8.8	10.5	8.1	4.9	9.4	6.4
Minimum (mg/L)	3.1	4.4	3.1	4.9	6.9	5.1
Number not detected (#ND)	0	0	0	0	0	0
Percent not detected (%ND)	0	0	0	0	0	0
Number > 20 mg/L HA (#)	49	17	30	1	1	0
Percent > 20 mg/L HA (%)	27	23	34	20	25	0

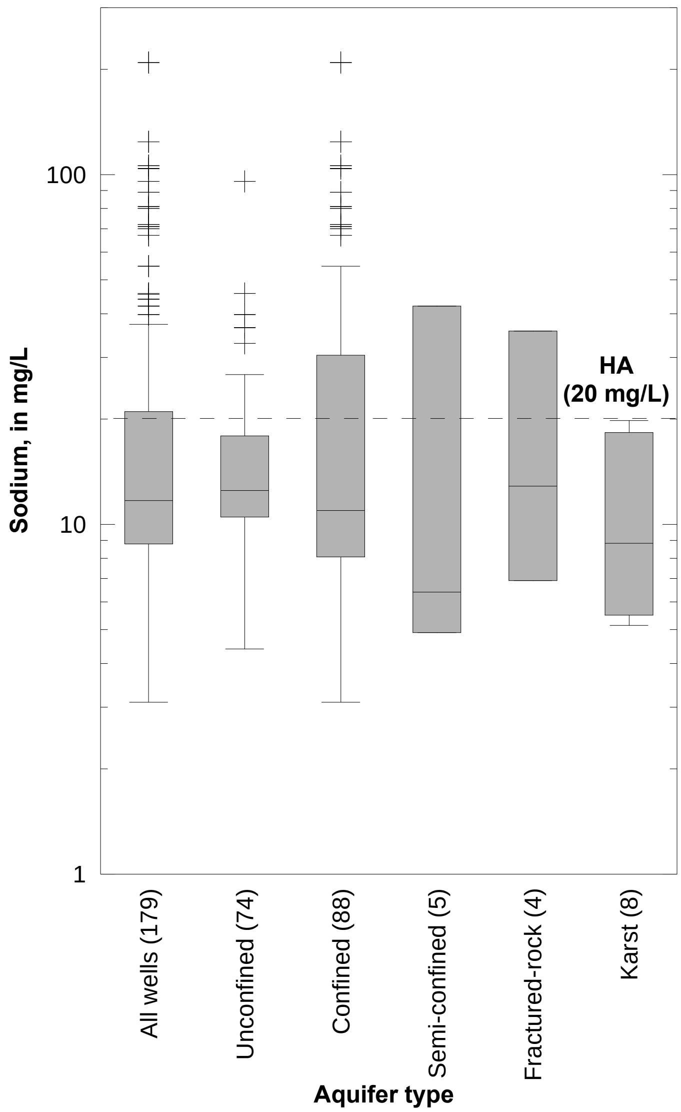


Figure 11. Percentile diagrams of sodium data by aquifer type. [mg/L, milligrams per liter; crosses, outliers; (#), number of samples; HA, health advisory for public water-supply systems (U.S. EPA, 2011).]

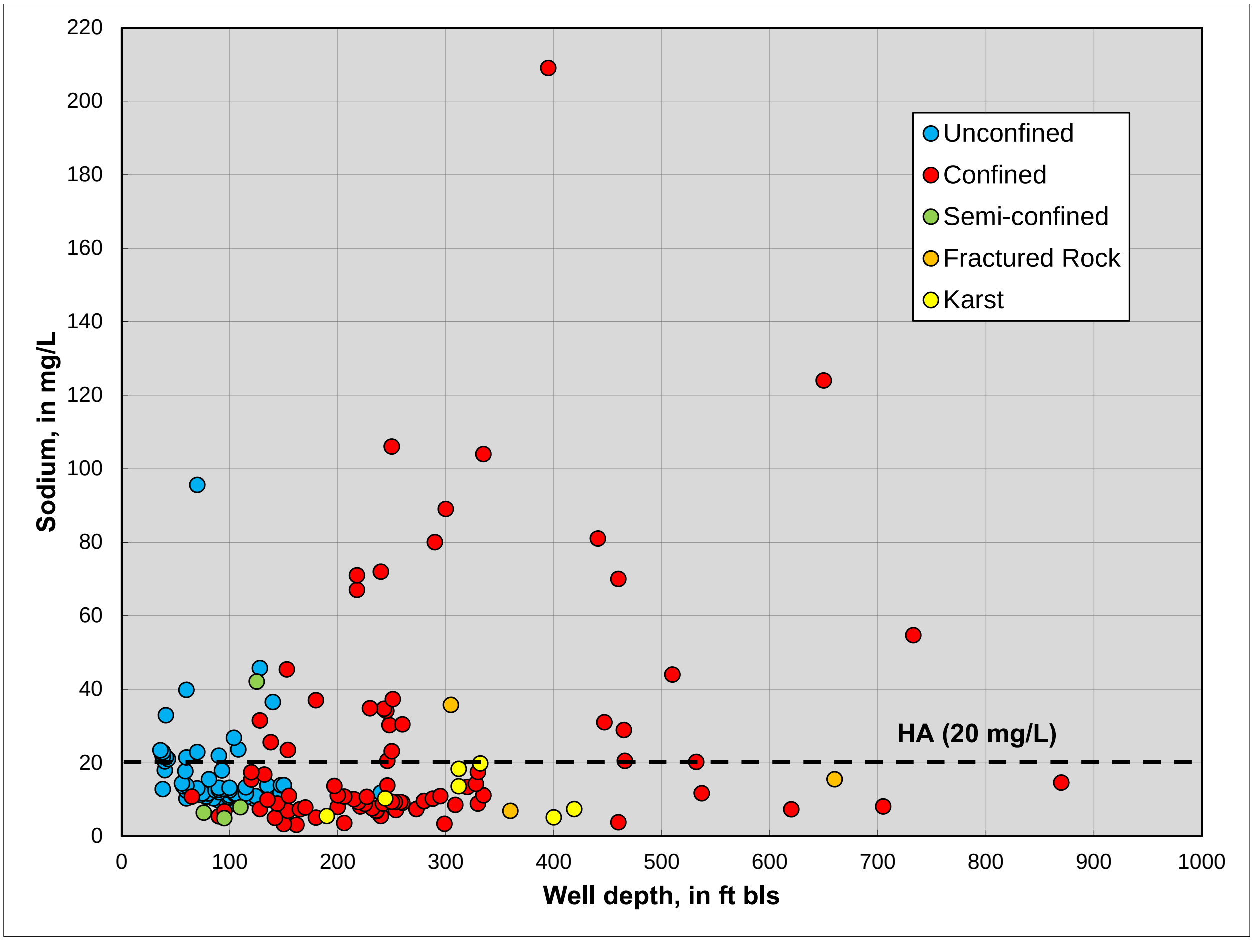


Figure 12. Scatter plot of sodium versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface; HA, health advisory for public water-supply systems (U.S. EPA, 2011).]

Iron

Overall, 796 iron analyses are in the SDWIS query provided to DNREC. Of these, 280 (35%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 190 iron analyses where aquifer type is known (Table 6). This number translates to ~20% of the total number of wells (948) where aquifer type is known (Figure 2). Overall, iron concentrations ranged from nondetectable to 12.2 mg/L with a median value of 0.05 mg/L (Table 6 and Figure 13). Iron was not detected above the laboratory quantitation limit in 74 (39%) of the 190 analyses. Iron concentrations exceeded the SMCL (0.3 mg/L) in 62 (33%) of the 190 samples (Table 6).

Confined, semi-confined, and fractured-rock wells had the highest median iron concentrations (0.14, 0.93, and 0.25 mg/L, respectively) and the largest fractions of concentrations above the SMCL (43, 60, and 50%, respectively; Table 6 and Figure 13). (Semi-confined and fractured rock wells, however, are not well represented with only 5 and 4 samples, respectively.) The most elevated iron concentration (12.2 mg/L) was associated with a confined well. Unconfined wells had the lowest median iron concentration (nondetectable) and the largest fraction of nondetectable concentrations (62%). Iron concentrations exceeded the

SMCL in 20% of the unconfined-well samples, a fraction that is higher than, but in general agreement with, Ferrari (2001; 17%) and Reyes (2010; 13%). Karst wells had the second-lowest median iron concentration (0.01 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 above laboratory quantitation limit; SMCL, secondary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2011).]

Statistics	All Wells	Unconfined Wells	Confined Wells	Semi-Confined Wells	Fractured-Rock Wells	Karst Wells
Number of wells/samples (#)	190	76	97	5	4	8
Percent of total (%)	100	40	51	3	2	4
Maximum (mg/L)	12.20	8.40	12.20	2.80	3.61	0.05
75th percentile (mg/L)	0.79	0.12	3.01	2.30	1.27	0.02
50th percentile (mg/L)	0.05	ND	0.14	0.93	0.25	0.01
25th percentile (mg/L)	ND	ND	0.01	0.11	ND	ND
Minimum (mg/L)	ND	ND	ND	ND	ND	ND
Number not detected (#ND)	74	47	21	1	2	3
Percent not detected (%ND)	39	62	22	20	50	38
Number > 0.3 mg/L SMCL (#)	62	15	42	3	2	0
Percent > 0.3 mg/L SMCL (%)	33	20	43	60	50	0

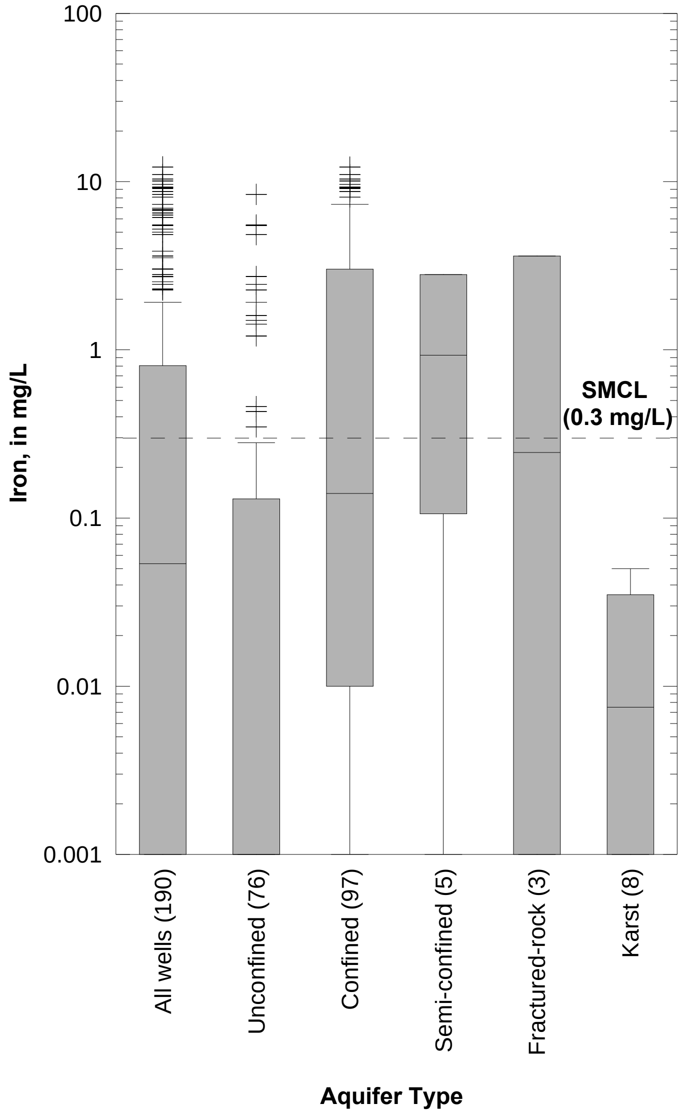


Figure 13. Percentile diagrams of iron data by aquifer type. [mg/L, milligrams per liter; crosses, outliers; (#), number of samples; SMCL, secondary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2011); nondetects assigned values of 0.001 mg/L to allow display on semi-logarithmic plot.]

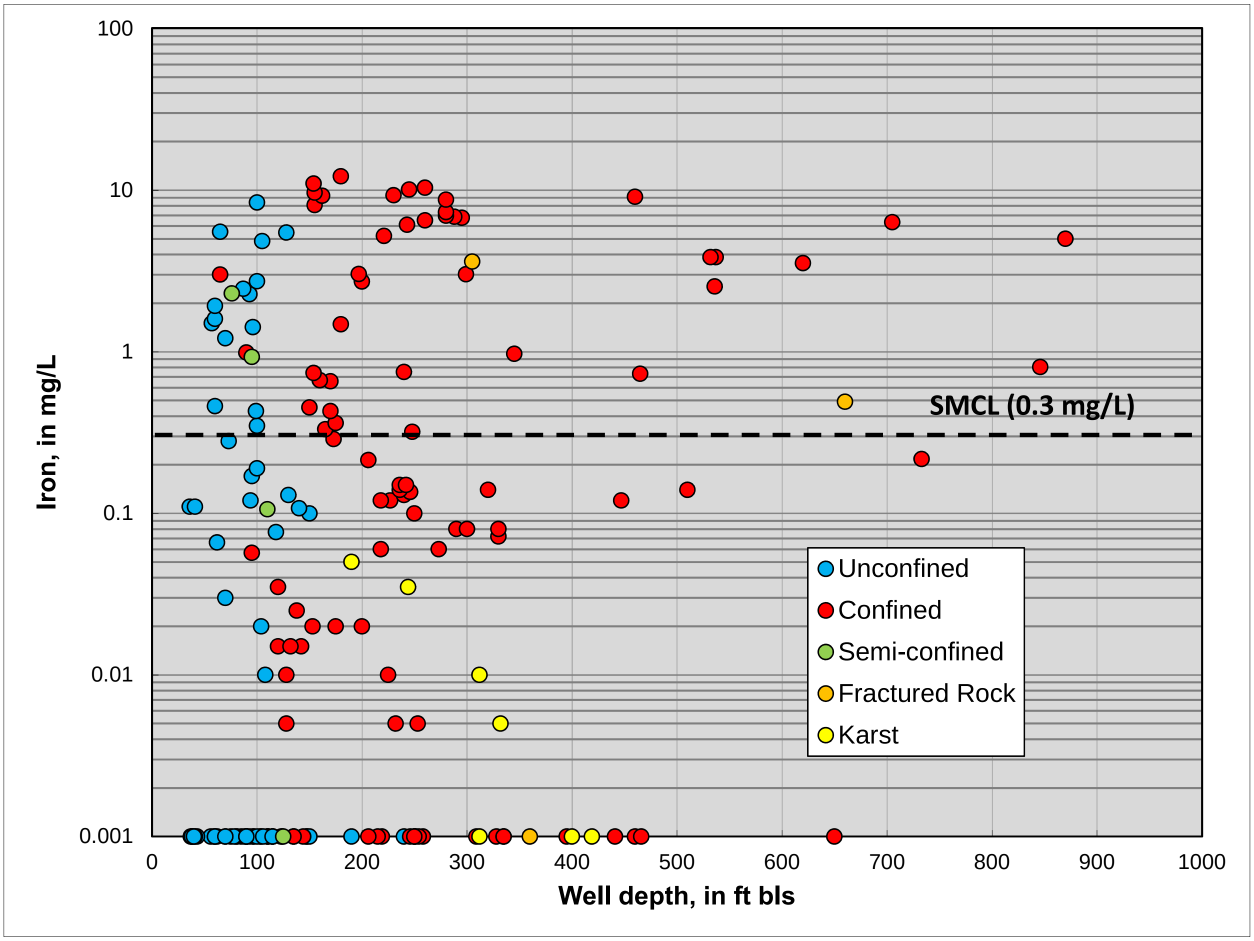


Figure 14. Scatter plot of iron versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface; SMCL, secondary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2011); nondetects assigned values of 0.001 mg/L to allow display on semi-logarithmic plot.]

Hardness as $CaCO_3$

Overall, 434 hardness as $CaCO_3$ ("hardness") analyses are in the SDWIS query provided to DNREC. Of these, 194 (45%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 194 hardness analyses where aquifer type is known (Table 7). This number translates to ~20% of the total number of wells (948) where aquifer type is known (Figure 2). Overall, hardness concentrations ranged from nondetectable to 380 mg/L with a median value of 43.1 mg/L (Table 7 and Figure 15). Hardness was not detected above the laboratory quantitation limit in 4 (2%) of the 168 analyses. With respect to the hardness scale of Love (1962), most of the analyses (147 or 87%) were classified as soft or moderately hard (Table 7). The remaining 13% of the analyses were classified as either hard (8%) or very hard (5%).

Karst wells had the highest median hardness concentration (262 mg/L) and the largest (and only) fraction of concentrations (100%) 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 typically in sharp contrast (Werkheiser, 1995); however, there are very limited data for fractured-rock wells in this assessment. Confined wells and semi-confined wells had similar median hardness concentrations (78 and 81 mg/L, respectively). Most of the confined well samples were classified as soft (36%) or moderately hard (48%) with the remainder classified as hard (16%); all of the semi-confined samples were classified as moderately hard (Table 7 and Figure 15). Unconfined wells had the lowest median hardness concentration (20.4 mg/L) and the largest fraction of results classified as soft (89%). Overall, there is no apparent trend in hardness with depth (Figure 16). At depths shallower than 150 ft bls, however, groundwater was always classified as either soft or moderately hard. Most of the deeper (>400 ft bls) confined well samples classified as soft are associated with the Potomac aquifer system.

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 (#)	168	76	77	5	2	8
Percent of total (%)	100	45	46	3	1	5
Maximum (mg/L)	380.0	148.0	172.0	100.0	74.0	380.0
75th percentile (mg/L)	87.1	31.6	90.6	81.3	71.7	366.8
50th percentile (mg/L)	43.1	20.4	78.0	81.0	69.5	262.0
25th percentile (mg/L)	20.2	12.9	48.0	74.2	67.2	250.0
Minimum (mg/L)	ND	ND	ND	62.5	64.9	220.0
Number not detected (#ND)	4	3	1	0	0	0
Percent not detected (%ND)	2	4	1	0	0	0
Soft; 0-60 mg/L (#)	96	68	28	0	0	0
Soft; 0-60 mg/L (%)	57	89	36	0	0	0
Mod. hard; 61-120 mg/L (#)	51	7	37	5	2	0
Mod. hard; 61-120 mg/L (%)	30	9	48	100	100	0
Hard; 121-180 mg/L (#)	13	1	12	0	0	0
Hard; 121-180 mg/L (%)	8	1	16	0	0	0
Very hard; >180 mg/L (#)	8	0	0	0	0	8
Very hard; >180 mg/L (%)	5	0	0	0	0	100

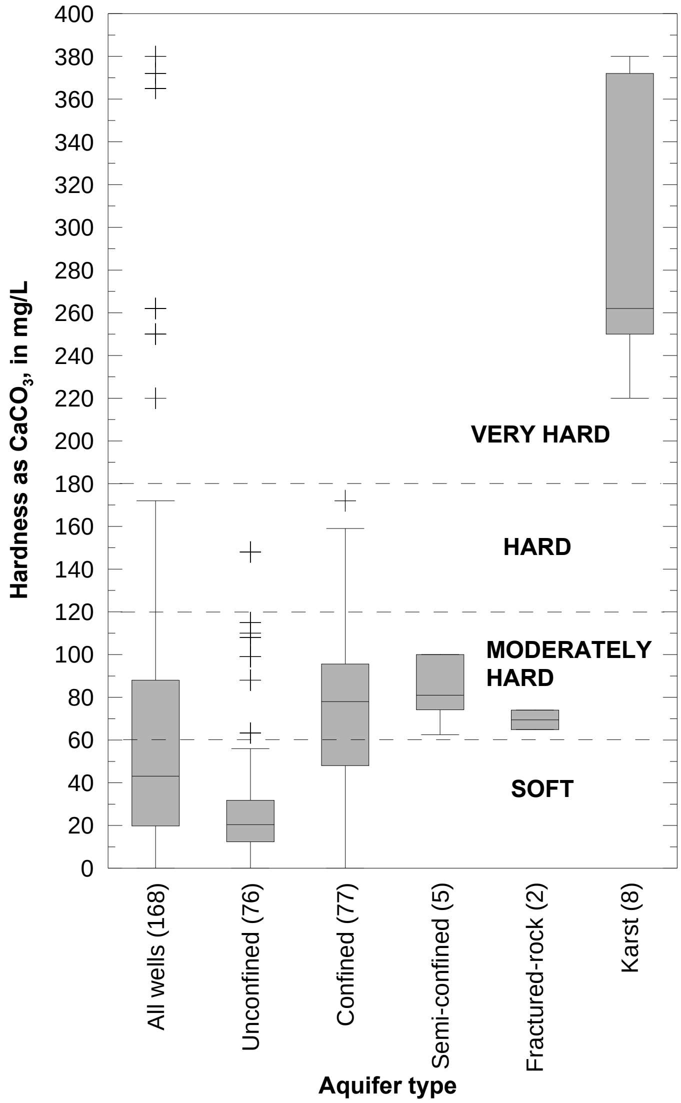


Figure 15. Percentile diagrams of hardness data by aquifer type. [mg/L, milligrams per liter; crosses, outliers; (#), number of samples; hardness scale after Love (1962).]

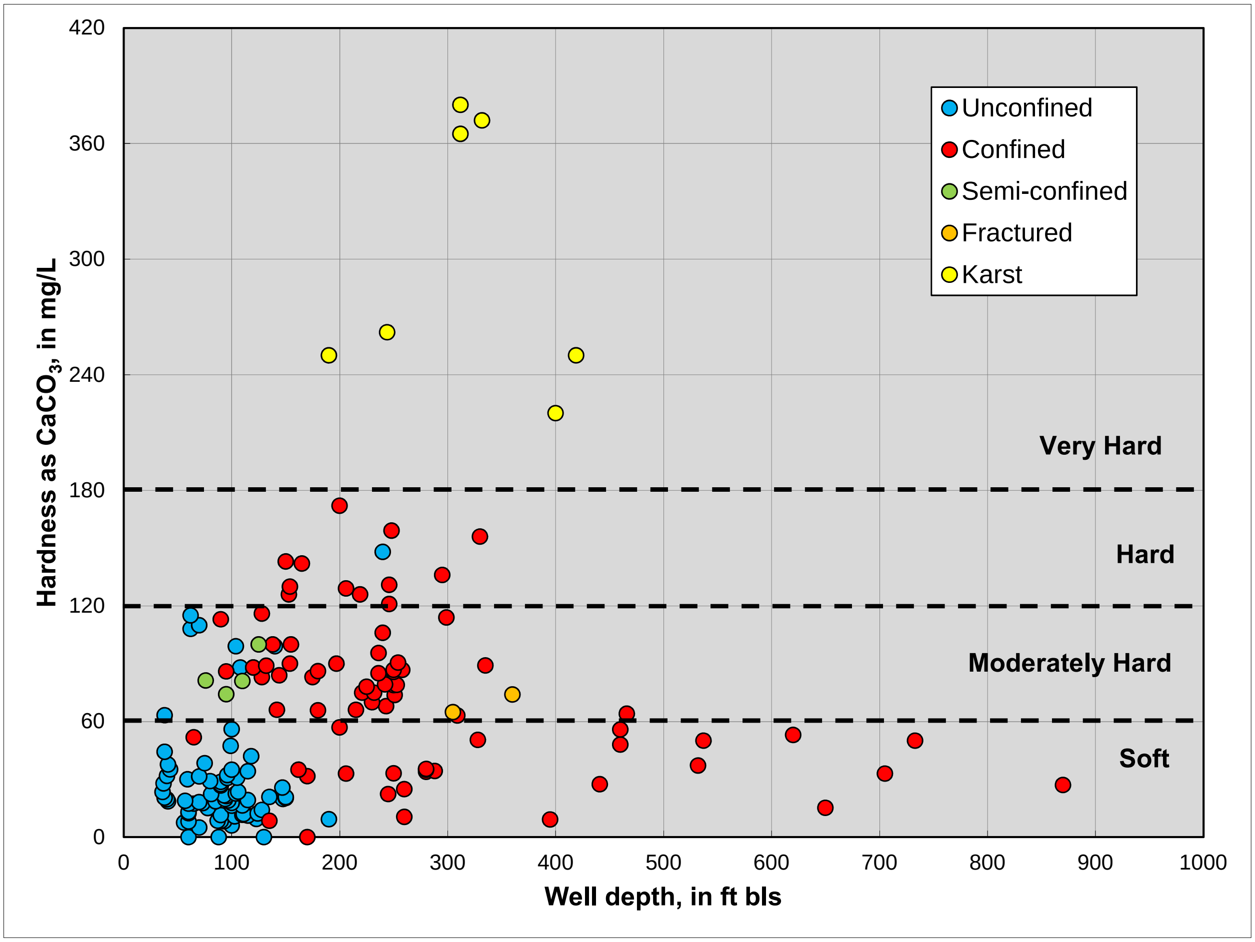


Figure 16. Scatter plot of hardness versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface; hardness scale after Love (1962).]

pH

Overall, 776 pH analyses are in the SDWIS query provided to DNREC. Of these, 197 (25%) could be linked by DNREC ID. Duplicate analyses for individual wells were averaged resulting in 162 pH analyses where aquifer type is known (Table 8). This number translates to ~17% of the total number of wells (948) where aquifer type is known (Figure 2). Overall, pH ranged from 4.8 to 8.7 standard units (S.U.) with a median value of 6.5 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 78 (~48%) of the 162 samples (Table 8). Only three pH values exceeded the upper limit of the SMCL range.

Karst and confined wells had the highest median pH values (7.8 and 7.4 S.U., respectively) and the largest fractions of samples within the SMCL range (100 and 73%, respectively; Table 8). Based on limited data (4 results), semi-confined wells had a relatively lower median pH value (6.5 S.U) and a smaller fraction of samples within the SMCL range (50%). 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 (5.8 S.U.) and the largest fraction of values below 6.5 S.U. and outside the SMCL range (86%; Table 8 and Figure 17). With only four results, pH data for fractured-rock wells are limited; the median pH was 6.2 S.U. with 75% of the results below the SMCL range (Table 8 and Figure 17). Overall, pH values below 6.5 S.U. occurred at nearly all depths, but were most prevalent at depths of ~200 ft bls and 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, 2011).]

Statistics	All Wells	Unconfined Wells	Confined Wells	Semi-Confined Wells	Fractured-Rock Wells	Karst Wells
Number of wells/samples (#)	162	62	84	4	4	8
Percent of total (%)	100.0	38.3	51.9	2.5	2.5	4.9
Maximum (S.U.)	8.7	7.5	8.7	8.3	8.1	7.9
75th percentile (S.U.)	7.6	6.0	8.1	7.4	6.8	7.8
50th percentile (S.U.)	6.5	5.8	7.4	6.5	6.2	7.8
25th percentile (S.U.)	5.8	5.5	6.5	5.9	6.1	7.6
Minimum (S.U.)	4.8	4.8	5.4	5.8	5.9	7.3
pH <6.5 SMCL (#)	78	53	20	2	3	0
pH <6.5 SMCL (%)	48.1	85.5	23.8	50.0	75.0	0.0
pH 6.5 to 8.5 (#)	81	9	61	2	1	8
pH 6.5 to 8.5 (%)	50.0	14.5	72.6	50.0	25.0	100.0
pH >8.5 SMCL (#)	3	0	3	0	0	0
pH >8.5 SMCL (%)	1.9	0.0	3.6	0.0	0.0	0.0

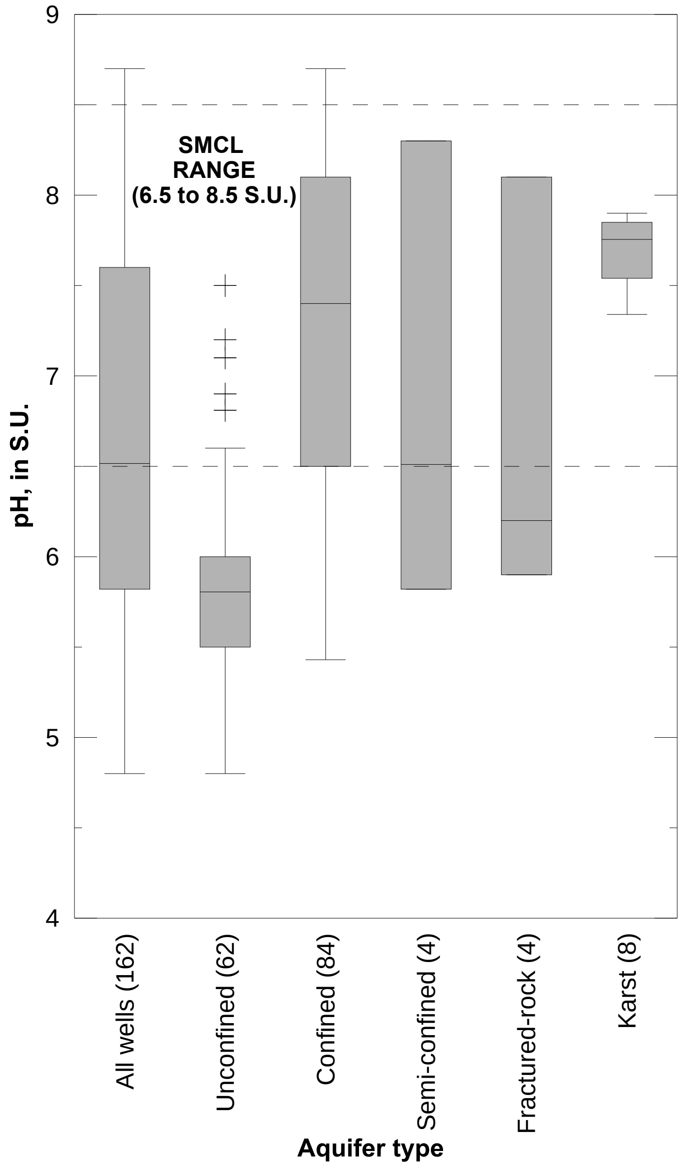


Figure 17. Percentile diagrams of pH data by aquifer type. [S.U., standard units; crosses, outliers; (#), number of samples; SMCL, secondary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2011).]

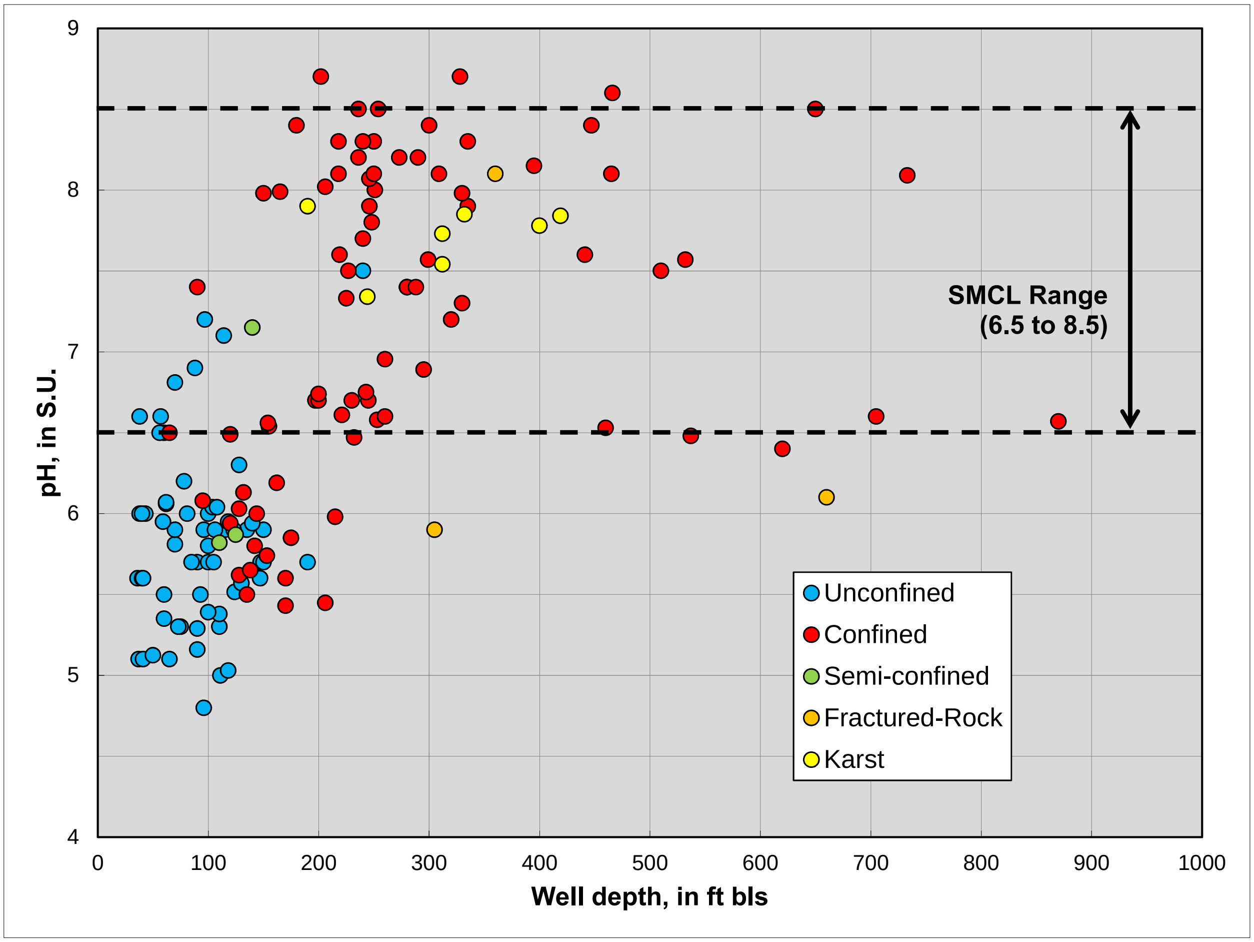


Figure 18. Scatter plot of pH versus well depth. [S.U., standard units; ft bls, feet below land surface; SMCL, secondary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2011).]

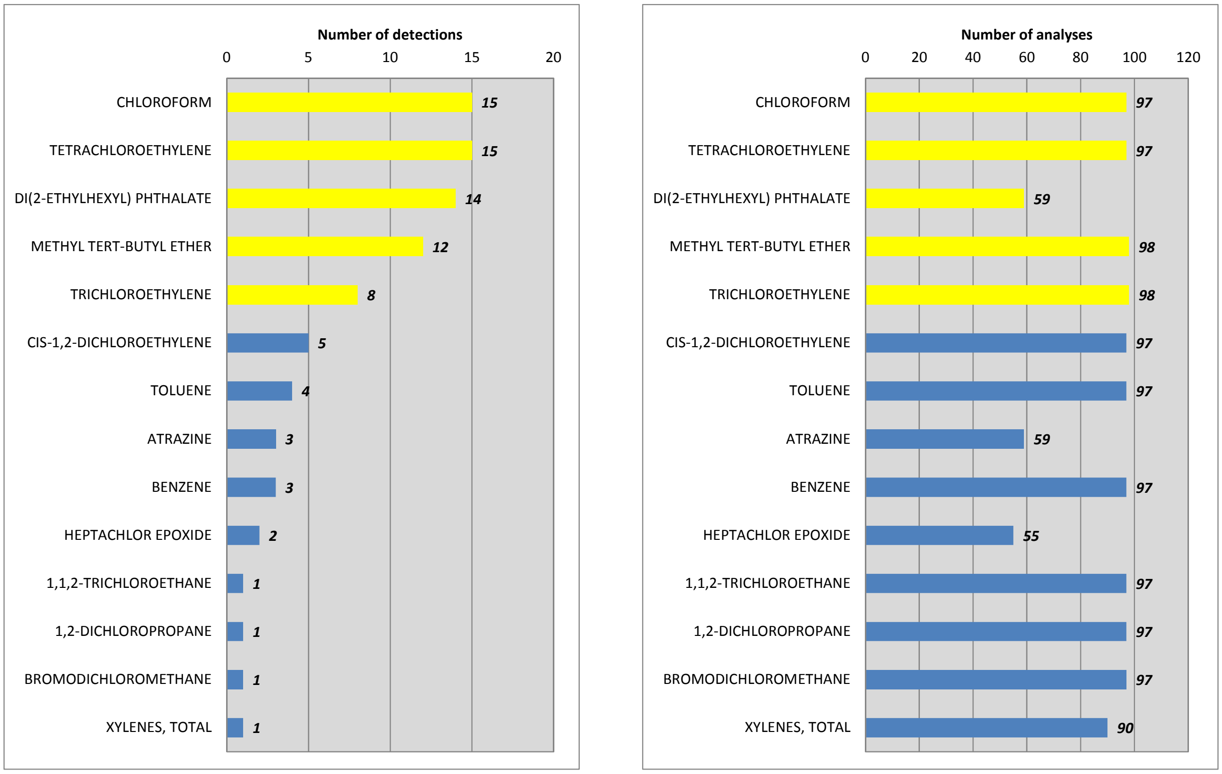
Organic compounds

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, 35,074 OC analyses are in the SDWIS query provided to DNREC. Duplicate analyses for individual wells were averaged resulting in 4,292 OC analyses. OCs were not detected in 4,207 (98%) of the 4,292 analyses. Out of the 57 organic compounds analyzed, 14 (25%) were detected (Figure 19).

Of the 85 OC detections, almost half (37 or 44%) were found at concentrations less than 1 µg/L. Chloroform, a disinfection byproduct, was the most-frequently detected OC, consistent with studies by Ferrari (2001) and Reyes (2010) involving water-quality data for 30 unconfined public water-supply wells in Delaware and DNREC's 2008 and 2010 305(b) groundwater-quality assessments (Kasper, 2008, 2010; Figure 19). Tetrachloroethylene (PCE), a solvent, was the second most-frequently detected OC (Figure 19). Di (2-ethylhexyl)-phthalate (DEHP), a plasticizer and common laboratory contaminant, was the third most-frequently detected OC.

PMCLs were exceeded in 13 (0.3%) of the 4,292 analyses. The following five analytes were found above the PMCL: tetrachloroethylene (PCE; 7 exceedences), methyl tert-butyl ether (MTBE; 3 exceedences), trichloroethylene (TCE; 1 exceedence), di(2-ethylhexyl)-phthalate (1 exceedence), and chloroform (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 Delaware (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 the findings of Ferrari (2001), Reyes (2010), and DNREC's 2008 and 2010 305(b) groundwater-quality assessments (Kasper, 2008, 2010). Well depths were established for 95 MTBE, 95 TCE, and 94 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, 2010). TCE and PCE, however, were detected at greater depths, the deepest of which was a PCE detection in a 253-ft deep confined well (Figure 20). Concentrations of MTBE and TCE above the PMCL were limited to depths of 100 ft bls and shallower; PCE, however, was found above the PMCL at greater depths, with the deepest PMCL exceedence associated with a 244-ft deep karst well (Figure 20). 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.



(A) **(B)**

Figure 19. Frequency distributions of organic compound (A) detections and (B) analyses. [Bars highlighted yellow indicate one or more concentration above the PMCL or primary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2011).]

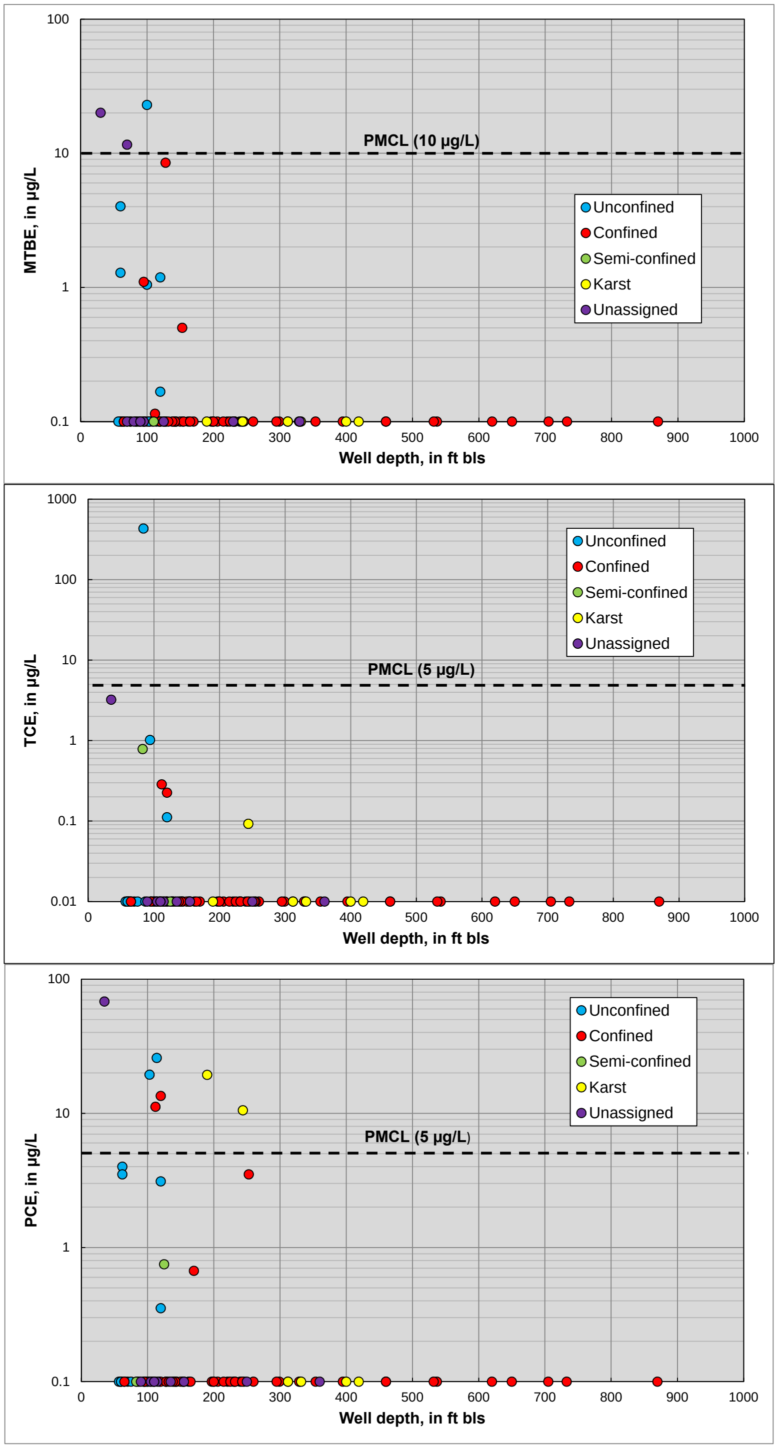


Figure 20. Scatter plots of methyl tert-butyl ether (MTBE), trichloroethylene (TCE), and tetrachloroethylene (PCE) versus well depth. [µg/L, micrograms per liter; ft bls, feet below land surface; PMCLs, primary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2011); nondetectable concentrations (zeros) assigned values of 0.1 or 0.01 µg/L to allow display on semi-logarithmic plots.]

Trace elements

For this assessment, trace elements are limited to the following analytes with PMCLs (DHSS, 2005; U.S. EPA, 2011): antimony (0.006 mg/L), arsenic (0.010 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, 2011).) Overall, 3,114 trace-element analyses are in the SDWIS query provided to DNREC. Duplicate analyses for individual wells were averaged resulting in 1,333 trace-element analyses. Trace elements were not detected in 993 (74%) of the 1,333 analyses.

Detectable trace-element concentrations were less than 0.1 mg/L in 251 (68%) of the 340 detections and less than 1 mg/L in 334 (98%) of the 340 detections. Barium, nickel, and chromium were the three most-frequently detected trace elements (Figure 21). (Although fluoride had one of the largest number of detections (79), it also had the largest number of analyses (211) and it was detected in a relatively smaller fraction (37%) of analyses (Figure 21).) Barium was detected in 79 (78%) of the 101 analyses, nickel was detected in 50 (50%) of 101 analyses, and chromium was detected in 48 (48%) of 101 analyses (Figure 21). Lead was detected in 33 (63%) of the 52 analyses (Figure 21). PMCLs or action levels were exceeded in 2 (0.2%) of the 1,333 analyses. Arsenic was the only analyte found above the PMCL.

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 (18%) of 102 analyses (Figure 21). Overall, concentrations ranged from nondetectable to 0.0145 mg/L. As previously noted, arsenic exceeded the PMCL (0.01 mg/L) in two wells or ~2% of the 102 analyses. Aquifer type was established for 93 (91%) of the 102 analyses. Of these 93 analyses, 23 were associated with unconfined wells, 2 were associated with a semi-confined wells, 60 were associated with confined wells, and 8 were associated with karst wells; no data were associated with fractured-rock wells. Arsenic detections are primarily associated with confined wells greater than 200 ft deep (Figure 22). One of the two samples with arsenic above the PMCL was associated with a confined well screened in the Rancocas aquifer, which contains the mineral glauconite (Figure 22). Although aquifer type was unassigned for the remaining sample with arsenic above the PMCL (Figure 22), that sample is also associated with a confined well screened in the Rancocas aquifer based on well construction information and geographic location. All of the confined wells with arsenic detections produce from either the Rancocas, Mt. Laurel, or Piney Point aquifers, which are associated with glauconitic geologic formations (Ramsey, 2005, 2007).

These findings are consistent with Drummond and Bolton (2010). Arsenic was detected at very low concentrations in two (9%) of the 23 unconfined well samples. Arsenic was not detected in semi-confined or karst wells.

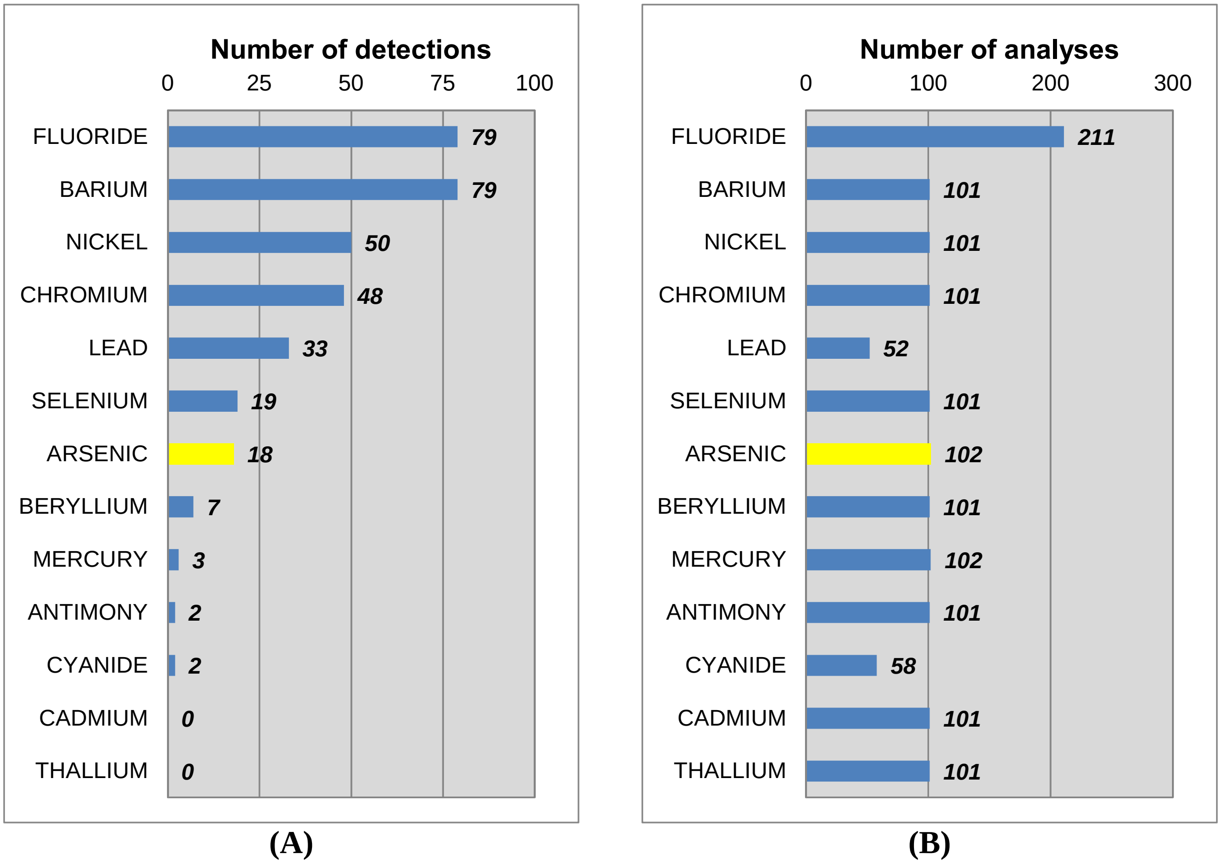


Figure 21. Frequency distributions of trace element (A) detections and (B) analyses. [Bars highlighted yellow indicate one or more concentration above the PMCL or primary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2011).]

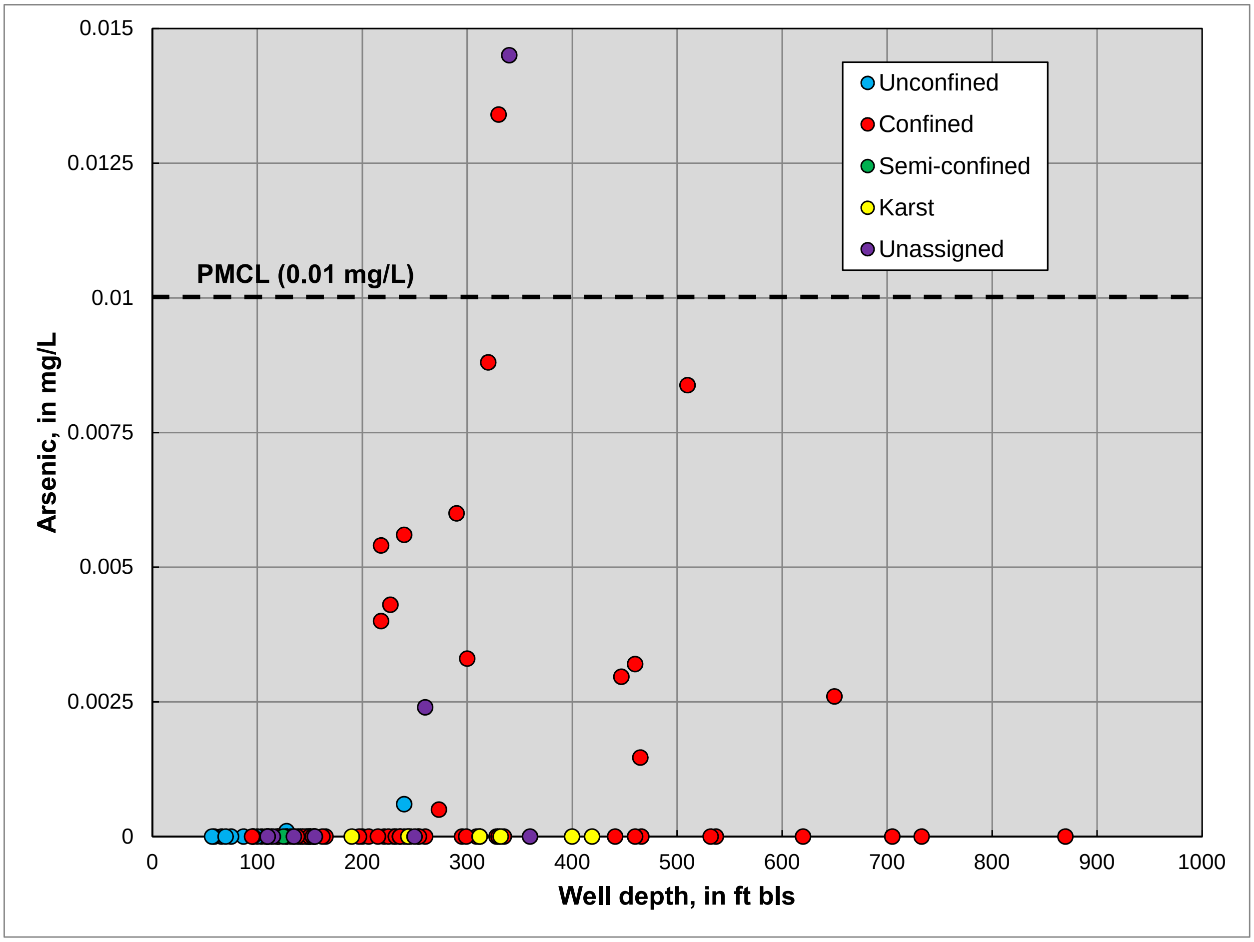


Figure 22. Scatter plot of arsenic versus well depth. [mg/L, milligrams per liter; ft bls, feet below land surface; PMCL, primary maximum contaminant level for public water-supply systems (DHSS, 2005; U.S. EPA, 2011).]

Radionuclides

Radionuclide data are limited to the following parameters: uranium-234, uranium-238, radium-226, and radium-228. The PMCL for uranium is 0.03 mg/L and the PMCL for radium-226 and radium-228 combined is 5 pCi/L (DHSS, 2005; U.S. EPA, 2011). Overall, 824 radionuclide analyses are in the SDWIS query provided to DNREC. Duplicate analyses for individual wells were averaged resulting in 78 radionuclide analyses, which are summarized as follows: uranium-234 (1 analysis), uranium-238 (43 analyses), radium-226 (17 analyses), and radium-228 (17 analyses). None of the uranium concentrations exceeded the 0.03 mg/L PMCL. Individually, none of the radium-226 or radium-228 activities exceeded the 5 pCi/L PMCL; however, 4 of the radium-226 and radium-228 combined results exceeded the PMCL. 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 2010-11 from public water-supply wells. The results of this assessment serve as "Part IV: Groundwater Assessment" of Delaware's overall 2012 305(b) report (DNREC, 2012). 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 (50,705 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, 2011; 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 February 2012, there were 1,158 active public water-supply wells in Delaware and aquifer type has been established for 948 (82%) of these wells. Most of the wells (77%) produce from Coastal-Plain aquifers while a much smaller percentage of the wells (5%) produce from Piedmont aquifers. General statistics on aquifer type for the 1,158 active wells follow: unconfined wells (409 or 35%), confined wells (428 or 37%), semi-confined wells (50 or 4%), fractured-rock wells (50 or 4%), and karst wells (11 or 1%). Aquifer type is not known or has not yet been established for the remaining 210 or 18% of the wells. (Percentages may not total 100% due to rounding.) Well depths range from 22 to 957 ft below land surface (bls) with a median well depth of 138 ft bls.

Overall, groundwater is predominantly soft or moderately hard based on the hardness scale of Love (1962). Specifically, most of the results (87%) 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 (98%), confined wells (84%), semi-confined wells (100%), and fractured-rock wells (100%). In contrast, all of the hardness results for karst wells were classified as very hard. Groundwater is partially 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 ~48% of the samples. Unconfined, semi-confined, and fractured-rock wells had the largest fractions of pH values below the SMCL range (86, 50, and 75%, respectively); in contrast, confined and karst wells had pH values that were predominantly within the SMCL range (73 and 100%, respectively). Overall, iron exceeded the 0.3 mg/L SMCL in a considerable fraction of the samples (33%) and was found above the SMCL in all aquifer types and at virtually all depths. Confined, semi-confined, and fractured-rock wells, however, had the largest fractions of concentrations greater than the SMCL (43, 60 and 50%, respectively). Groundwater is generally dilute overall with a median total dissolved solids (TDS) concentration of 156 mg/L. TDS concentrations exceeded the 500 mg/L SMCL in a small fraction (2%) of the samples. Karst wells had the highest median TDS concentration (403 mg/L) and the largest fraction of concentrations above the SMCL (25%). Chloride concentrations never exceeded the SMCL (250 mg/L). The most elevated chloride concentration (177 mg/L) was associated with an unconfined well sample. Karst wells had the highest median chloride concentration (48.3 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 (27%) and at virtually all depths. Confined wells had the largest fraction of sodium concentrations above the HA (34%).

Nitrate was used as a proxy to indicate the extent of human influence on groundwater quality. Overall, most of the wells (55%) 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 (4.70 and 3.38 mg/L, respectively) and the largest fractions of concentrations greater than 0.4 mg/L (90 and 100%, respectively). The unconfined aquifer also had the most elevated nitrate concentration (27.5 mg/L) and the only concentrations above the 10 mg/L Primary Maximum Contaminant Level or PMCL (12%). Nitrate concentrations in the karst aquifer never exceeded the PMCL, however. Although data were limited to only six samples, the semi-confined aquifer had an intermediate median nitrate concentration (1.77 mg/L) with half of the concentrations greater than 0.4 mg/L. With only four samples, the fractured-rock aquifer also is not well represented in this assessment; the median nitrate concentration was nondetectable with 25% of the concentrations greater than 0.4 mg/L. Confined aquifers had the lowest median nitrate concentration (nondetectable) and the smallest fraction of concentrations greater than 0.4 mg/L (20%). Confined aquifers also had the largest fraction of nondetectable nitrate concentrations (78%). 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 the karst aquifer. At greater depths nitrate was rarely detected above the quantitation limit. Areally, PMCL exceedences were primarily limited to Sussex County with the exception of one exceedence in northern New Castle County.

Organic compounds (OCs) were not frequently detected and, when detected, rarely exceeded PMCLs. Specifically, OCs were not detected in 4,207 (98%) of 4,292 analyses. Of the 85 OC detections, almost half (37 or 44%) were found at concentrations less than 1 µg/L. Chloroform, a disinfection byproduct, was the most-frequently detected OC, consistent with Ferrari (2001), Reyes (2010), and Kasper (2008, 2010). PMCLs were exceeded in a very small fraction (13 or 0.3%). The following five analytes were found above the PMCL: tetrachloroethylene (PCE; 7 exceedences), methyl tert-butyl ether (MTBE; 3 exceedences), trichloroethylene (TCE; 1 exceedence), di(2-ethylhexyl)-phthalate (1 exceedence), and chloroform (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), Reyes (2010), and Kasper (2008, 2010), 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 detections 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 993 (74%) of 1,333 analyses. Of the 340 trace-element detections, 251 (68%) were found at concentrations less than 0.1 mg/L and 334 (98%) 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, 2010). PMCLs or action levels were exceeded in a very small fraction (2 or 0.2%) of the analyses. Arsenic was the only analyte found above the PMCL. Arsenic detections are primarily limited to confined wells greater than 200 ft deep that produce from the Rancocas, Mt. Laurel, or Piney Point aquifers, which are associated with glauconitic geologic formations (Ramsey, 2005, 2007). This finding is consistent with Drummond and Bolton (2010).

Radionuclide data were very limited in this assessment and available data were limited to the following parameters: uranium-234, uranium-238, radium-226, and radium-228. The PMCL for uranium (0.03 mg/L) was never exceeded. Four radium-226 and radium-228 combined results exceeded the 5 pCi/L PMCL.

This 305(b) groundwater-quality assessment is DNREC's third 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.

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