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TRENDS IN THE DEPTH, YIELD, AND WATER QUALITY OF WELLS IN VIRGINIA RELATED TO GEOLOGIC CONDITIONS

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INTRODUCTION

The Virginia Department of Mines, Minerals and Energy, Division of Geology and Mineral Resources (DGMR) periodically receives requests for information about ground water potential in Virginia. Some requests are regional in scope and made by companies seeking to locate new operations or developments in Virginia. Other requests are made by municipalities, established businesses, and private landowners seeking to establish, replace, or upgrade existing water supplies.

People requesting ground water information from DGMR generally understand that there is a relationship between geology and water quantity and quality. As a result, a company may want to know whether a formation will likely yield water above a threshold quantity or within certain quality parameters. In other cases, customers are interested in the physical characteristics of an aquifer. For example, an out-of-state consultant bidding on a job in Virginia may be interested in knowing how deep a well will probably need to be drilled, where water is likely to be encountered, and what type of drilling will be required. Occasionally, a homeowner in the process of drilling a well that is producing little water will want to know whether it is better to drill deeper or try a new location.

In order to provide a general idea of what to expect when drilling a water well in different geologic settings in Virginia, DGMR recently analyzed two datasets. The first dataset contains well location, construction, and initial yield data for 2,327 active and inactive public supply wells in Virginia, which include community and non-community systems (Virginia Department of Health unpublished data; Figure 1). The second dataset contains well locations and the results of water analyses for 3,844 domestic and public water supply wells collected as part of the National Uranium Resource Evaluation (NURE) program in the 1970's and 1980s (Smith, 1997; Figure 2).

Methodology

Well records in each dataset were assigned by well location to a geologic map unit from the 1993 geologic map of Virginia. This assignment was accomplished using the digital version of the map (DGMR, 2003) and reported coordinates for each well. After the geologic map units were assigned, each well record was further assigned to the appropriate geologic province and primary rock type category (Figure 3). Records were then grouped by geologic province and by rock type for statistical analysis, provided at least twenty records were available for each rock type. Minimum, maximum, mean, median, and 5th, 25th, 75th, and 95th percentile values were calculated for the following characteristics:

Public Well Dataset: total depth, casing depth, and yield.

NURE Dataset: pH, conductivity, concentrations of aluminum, chloride, fluoride, manganese, sodium, and uranium.

Limitations

The analyses in this report provide useful information, but have some significant limitations. First,

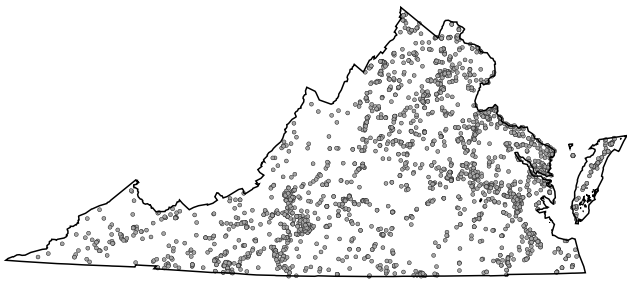


Figure 1. Spatial distribution of public supply wells that are analyzed in this report (Virginia Department of Health, unpublished data).

Figure 2. Spatial distribution of wells sampled for the NURE program that are analyzed in this report (Smith, 1997).

some of the locations of individual water wells may not be accurate. In addition, the 1993 Geologic Map of Virginia, which is published at a scale of 1:500,000, has rock formation contacts that vary in accuracy. As a result, it is probable that some well locations have been assigned to the wrong geologic map unit. Given the large number of samples, the effect of this error is not likely to be significant.

Second, map units for the 1993 Geologic Map of Virginia may contain more than one rock type. As a result, wells within a map unit may be drilled into different material than the primary rock type of the map unit. Third, the public well dataset is biased towards population centers, especially in the Coastal Plain province. Fourth, the initial tested well yields shown in the dataset may be higher than long term production yields. Long-term production from bedrock wells in extreme cases may decline to as little as 25 percent of initial yields (Tom Gathright, personal communication).

Fifth, the analysis does not consider the topographic setting of each well, which can affect well yield and construction characteristics, or the difference between surface and subsurface geology. Well screens in deeper wells in the Coastal Plain are likely in aquifers that are different than surface geologic units shown on the 1993 Geologic Map of Virginia. Important aquifers in the Coastal Plain province are described in several reports listed in the bibliography. Along the Fall Zone, which roughly parallels Interstate 95, Coastal Plain deposits shown on the geologic map are thin and wells are likely drilled through unconsolidated sediment into crystalline bedrock.

Sixth, the 1993 Geologic Map of Virginia does not show unconsolidated deposits of sediment west of the Coastal Plain province. As a result, this report could not consider known alluvial deposits along the west flank of the Blue Ridge. These thick deposits overlie carbonate bedrock, creating hydrogeologic conditions that allow wells to have higher yields.

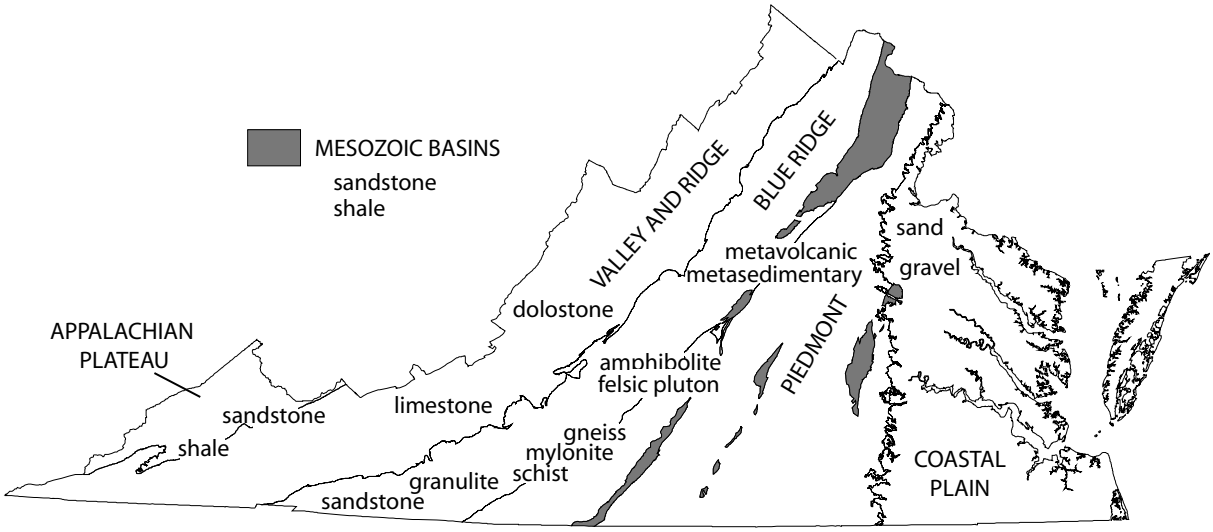


Figure 3. Geologic provinces in Virginia and major rock types into which well records and water analyses are grouped for this report.

Seventh, this report does not consider the affect of the Chesapeake Bay impact structure on ground-water quality in the Coastal Plain province. Eighth, well construction and yield data are from public water supplies, which are commonly drilled deeper to provide for additional yield and borehole storage. In addition, some existing high yield domestic or industrial wells may have been approved for and converted to public supply. Therefore, it is likely that the ranges of well depth, casing depth, and well yield would be lower in a similar analysis of domestic wells.

Ninth, only 18 well records were available in the public well dataset for the Appalachian Plateau province; the statistics for this province may change significantly with a larger dataset. Tenth, it is assumed that all water samples in the NURE dataset were collected from the well water system before undergoing any water treatment.

Finally, the data analysis is statewide in scope. It does not look at individual geologic formations, some of which are known to produce more or less water than other formations or have specific water quality problems. The report does not supersede the results of detailed regional or local groundwater studies in Virginia.

WELL CHARACTERISTICS

Well construction techniques vary across Virginia. In the Appalachian Plateau, Valley and Ridge, Blue Ridge, and Piedmont geologic provinces, water supply wells are normally drilled into bedrock using the air rotary method. Public supply wells require at least 50 feet of casing to seal off unconsolidated regolith from the well bore. The uncased bedrock portions of wells in these provinces are left open to allow water from intersecting fractures or solution cavities to enter the well. It is assumed in most wells that the uncased portion of the well bore is generally slightly smaller than the diameter of the casing. For example, a well with a six-inch casing would typically have a 5.25-inch well bore. In the Coastal Plain province, wells are typically drilled using the mud rotary method. The casing in these wells must extend the entire depth of the well to exclude unconsolidated material. The casing is screened or perforated in the intervals that coincide with aquifers, which are typically sand-, gravel- or shell-rich intervals. Geophysical logging is sometimes utilized to identify water-bearing zones in wells constructed in the Coastal Plain. The use of geophysical logging is uncommon in water wells in the rest of the state.

Casing Diameter

Casing diameter information is available for 2,012 public wells in the dataset. 1,931 of these wells have casing diameters that range from four to twelve inches. The remaining wells are smaller diameter drilled or driven wells and larger diameter bored wells. Wells with six-inch casings are the most common with 1,354 reported. Wells with four- and eight-inch casings are also common, with 224 and 248 records, respectively. Wells with ten- and twelve-inch casings are less common, with 62 total records. Wells with four-inch casings are most prevalent in the Coastal Plain province.

Total Depth

Well depth information is available for 2,248 wells (Table 1). The deepest well in the dataset is 1,077 feet deep and located in the Coastal Plain. Statewide, nine out of ten public wells are between 119 and 713 feet in total depth. The interquartile depth range (middle 50 percent) of these wells is between 250 and 455 feet. The median well depth is 330 feet. Wells with eight- and ten-inch diameter casings tend to be drilled deeper than wells with six-inch casings, with the median depth for a well with a ten-inch casing, at 425 feet, being approximately 100 feet deeper than that of a well with a six-inch casing. The median well depth for an eight-inch well is 350 feet. Median well depths range from 213 feet in the Appalachian Plateau to 365 feet in the Coastal Plain (Table 1). Well depth also varies by major rock type (Table 2).

Casing Depth

Casing depth information is available for 1,933 wells. Wells drilled in the Coastal Plain are usually cased for their entire depth; as a result, they are not compared to bedrock wells in provinces to the west. Casing depths in other provinces are generally consistent, with the exception of the Valley and Ridge province (Table 1). Median casing depths in the Appalachian Plateau, Blue Ridge, Piedmont, and Mesozoic Basins range from 55 to 69 feet. In the Valley and Ridge Province, the median casing depth of 100 feet is more than 30 feet deeper than the other provinces. Casing depth is consistent among most rock types, with median casing depths ranging from 55 to 63 feet (Table 2). Wells assigned to amphibolite, limestone, and dolostone rock types have median casing depths that range from 90 to 105 feet.

Property or Constituent	Appalachian Plateau									Blue Ridge									Coastal Plain								
	n	Mean	Percentile values							n	Mean	Percentile values							n	Mean	Percentile values						
			Min.	5%	25%	50%	75%	95%	Max.			Min.	5%	25%	50%	75%	95%	Max.			Min.	5%	25%	50%	75%	95%	Max.
Total Depth (ft)	17	261	63	105	195	213	342	441	550	623	344	56	138	250	320	405	605	835	765	400	53	94	255	365	536	786	1077
Casing Depth (ft)	16	86	28	43	50	55	113	183	200	514	71	8	50	52	60	79	118	520	678	285	19	54	155	270	382	587	995
Yield (gpm)	18	32	3	5	12	28	36	76	150	643	31	1	3	10	20	33	100	340	789	162	2	11	33	60	150	491	2200
pH (standard units)	200	7.0	4.3	5.7	6.7	7.1	7.5	8.1	8.9	494	6.6	5.1	5.7	6.2	6.5	6.9	7.5	8.9	1129	6.5	4.2	5.1	5.8	6.4	7.2	8.3	8.9
Specific cond. (µS/cm at 25°C)	200	206	15	49	136	200	263	381	890	494	99	5	20	40	70	132	269	770	1129	244	20	48	100	180	301	580	4050
Aluminum (ppb)	199	86	9	20	41	60	95	161	1466	485	36	3	10	15	22	37	114	328	1115	199	8	24	77	123	187	572	3825
Chloride (ppm)	199	10	2	3	4	5	9	27	191	462	8	2	3	4	5	8	21	73	1097	20	1	3	6	11	19	52	1120
Fluoride (ppb)	171	96	10	23	51	79	110	218	811	262	94	7	13	28	48	75	289	2065	611	414	9	16	34	74	355	2199	5746
Manganese (ppb)	173	228	9	25	70	143	297	644	3798	391	52	1	4	12	27	58	174	1406	1045	84	2	16	45	66	93	176	3911
Sodium (ppm)	199	15.2	2.2	3.3	6.3	10.5	17.8	41.0	118.2	439	5.0	0.2	1.2	2.4	3.7	5.7	13.9	32.2	1087	28.6	0.2	3.1	9.4	13.7	24.7	119.4	466.6
Uranium (ppb)	201	0.08	0.00	0.00	0.00	0.01	0.03	0.08	5.0	494	0.07	0.00	0.00	0.01	0.02	0.04	0.23	6.1	1130	0.08	0.00	0.00	0.00	0.02	0.05	0.20	15.4

Property or Constituent	Mesozoic Basins									Piedmont									Valley and Ridge								
	n	Mean	Percentile values							n	Mean	Percentile values							n	Mean	Percentile values						
			Min.	5%	25%	50%	75%	95%	Max.			Min.	5%	25%	50%	75%	95%	Max.			Min.	5%	25%	50%	75%	95%	Max.
Total Depth (ft)	108	383	60	149	245	359	490	715	1003	394	333	58	125	245	305	400	586	1045	341	365	14	125	250	340	460	700	1050
Casing Depth (ft)	102	68	50	50	53	58	72	120	150	344	77	29	50	55	69	90	125	405	279	119	14	50	60	100	143	291	580
Yield (gpm)	116	62	1	5	16	38	85	200	325	409	35	1	4	12	22	42	101	350	352	104	1	6	20	40	86	350	3500
pH (standard units)	117	7.2	5.8	6.0	6.8	7.3	7.7	8.1	9.3	935	6.5	4.5	5.6	6.1	6.4	6.8	7.7	9.9	967	7.4	3.7	6.2	7.1	7.4	7.7	8.1	9.8
Specific cond. (µS/cm at 25°C)	117	247	35	46	125	227	310	472	1000	935	114	5	29	51	83	130	300	998	967	312	10	67	180	280	410	617	3420
Aluminum (ppb)	112	56	7	13	20	38	74	151	323	904	50	2	11	16	25	49	153	1182	955	54	3	10	21	38	64	142	1997
Chloride (ppm)	110	14	4	5	7	9	17	34	67	872	10	1	4	5	7	11	27	163	893	8	1	3	4	5	9	25	117
Fluoride (ppb)	54	191	14	17	32	79	187	633	2838	392	67	1	13	26	45	72	173	1279	605	128	2	16	33	58	111	402	4548
Manganese (ppb)	65	85	3	10	40	69	126	198	308	738	50	0	5	14	37	63	139	605	586	143	2	12	50	102	181	394	3172
Sodium (ppm)	109	11.7	1.4	3.2	6.7	9.5	13.1	25.5	87.4	837	8.0	0.1	1.4	3.6	5.7	11.2	18.9	61.1	866	9.7	0.1	0.7	2.0	4.6	10.7	28.6	707.6
Uranium (ppb)	117	0.74	0.00	0.00	0.05	0.15	0.85	2.6	16.0	935	1.24	0.00	0.00	0.02	0.04	0.09	0.62	729	967	0.26	0.00	0.00	0.03	0.09	0.22	1.1	14.8

Table 1. Statistical summary of public supply well records (Virginia Department of Health, unpublished data) and NURE well water analyses (Smith, 1997) by geologic province.

Well Yield

Well yield information is available for 2,327 wells. The largest reported yield is 3,500 gallons per minute (GPM) from a well in the Valley and Ridge province. The statewide median well yield is two orders of magnitude lower at 33 GPM. The interquartile range of public wells in the entire dataset is between 15 and 75 GPM. One well in ten has a reported yield of less than 5 GPM or more than 273 GPM. Median well yield varies by province from 20 GPM in the Blue Ridge to 60 GPM in the Coastal Plain (Figure 4, Table 1).

Well yield varies by major rock type (Figure 4, Table 2). Highest median well yields, ranging from 57 to 63 GPM, are reported in wells drilled through unconsolidated sand and gravel formations in the Coastal Plain. Wells assigned to dolostone and limestone rock types in the Valley and Ridge province and shale rock types have median well yields ranging from 35 to 45 GPM, respectively. Median well yields in wells assigned to amphibolite, felsic pluton, gneiss, granulite, metasedimentary, mevavolcanic, sandstone, and schist rock types range from 18 to 27 GPM. Wells assigned to mylonite have the lowest median yield of 8 GPM.

Well yield also varies with casing diameter (Figure 5). Statewide, the median well yield for a well with a six-inch casing is 27 GPM. For a well with an eight-inch casing, it is 90 GPM. The median well yield for a well with a ten-inch casing is 173 GPM.

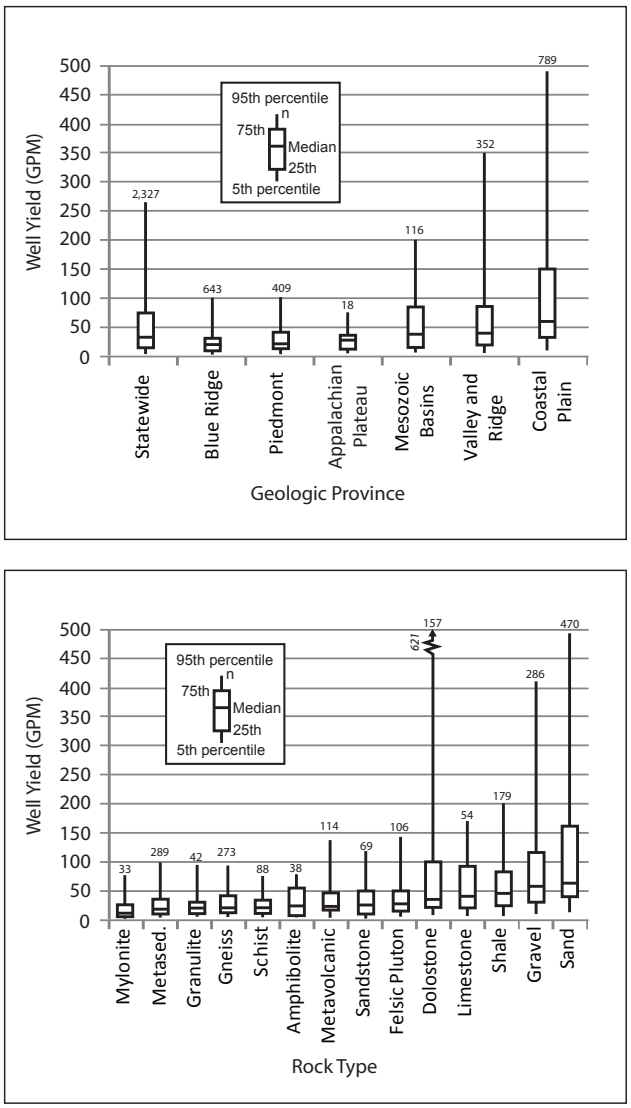


Figure 4. Variation in well yield by geologic province and major rock type.

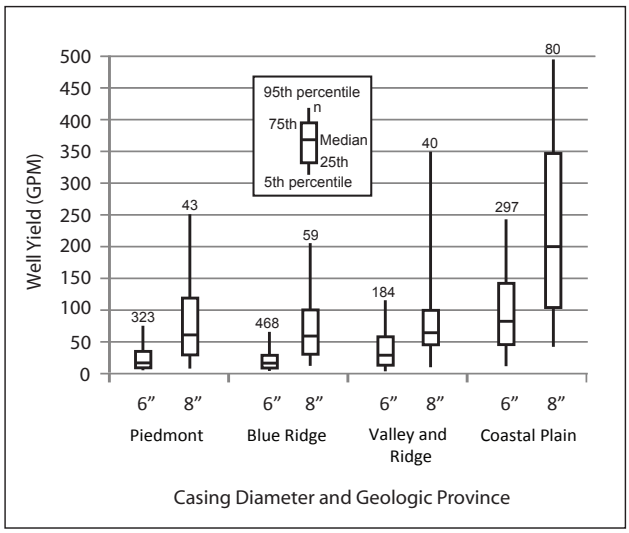


Figure 5. Variation in well yield among six- and eight-inch public supply wells in four geologic provinces in Virginia.

WATER QUALITY

pH

The NURE dataset contains the results of 3,842 pH measurements. The pH value of water indicates whether it is acidic (<7) or basic (>7). The Environmental Protection Agency (EPA) has established a secondary (aesthetic) standard for pH range of 6.5 - 8.5 for public water supplies (U.S. EPA, 2007). Water above or below this range may require treatment to reduce corrosion or mineral buildup. Water from approximately 38 percent of wells in the NURE dataset had a pH value below 6.5. Approximately one percent of water samples had a pH value above 8.5.

The pH of ground water in the Valley and Ridge province tends to be higher, with the interquartile range being slightly basic (Figure 6, Table 1). The pH of ground waters in the Blue Ridge and Piedmont are similar, with the interquartile range being slightly acidic. The interquartile range of water samples from wells in the Mesozoic Basins, Appalachian Plateau, and Coastal Plain straddle a neutral pH, with the median values ranging from acidic in the Coastal Plain to basic in the Appalachian Plateau and Mesozoic Basins. The range of reported pH values is greatest in water samples from wells drilled through sand and gravel formations of the Coastal Plain and most consistent in water samples from wells assigned to limestone, dolostone, and amphibolite (Figure 6, Table 2). Wells in areas underlain by limestone and dolostone have the highest pH values, with water samples from most wells being above 7 standard units.

Specific Conductance

Specific conductance measurements were recorded for 3,842 water well samples. Specific conductance is a measure of the ability of water to conduct electricity and relates to the amount of total dissolved solids (TDS) in water. The EPA has established a secondary standard for TDS of 500 milligrams per liter (mg/L) (U.S. EPA, 2007). Water with a TDS concentration above 500 mg/L has a greater potential to cause aesthetic problems such as scaling or bad taste. In natural waters, the value of TDS in mg/L is likely to be between 0.55 and 0.75 of the value of specific conductance in micro siemens (µS)/cm at 25°C (Hem, 1989). Based on this relationship, it is expected that

Property or Constituent	Amphibolite									Dolostone									Felsic Pluton									Gneiss									Granulite								
	n	Mean	Percentile values							n	Mean	Percentile values							n	Mean	Percentile values							n	Mean	Percentile values							n	Mean	Percentile values						
			Min.	5%	25%	50%	75%	95%	Max.			Min.	5%	25%	50%	75%	95%	Max.			Min.	5%	25%	50%	75%	95%	Max.			Min.	5%	25%	50%	75%	95%	Max.			Min.	5%	25%	50%	75%	95%	Max.
Total Depth (ft)	35	315	114	169	203	300	400	523	700	152	368	50	130	255	342	457	700	920	99	374	85	145	256	345	445	705	1045	266	339	56	141	260	320	405	585	705	40	322	80	147	209	300	401	600	700
Casing Depth (ft)	34	84	45	51	62	90	100	112	142	127	134	17	50	69	105	175	295	500	89	76	39	50	51	58	84	137	405	222	71	29	50	53	63	84	114	207	28	73	8	50	51	62	79	158	176
Yield (gpm)	38	33	2	4	7	23	55	78	115	157	152	2	8	20	35	100	621	3500	106	41	1	5	15	27	50	143	250	273	31	1	4	12	20	41	93	245	42	31	3	6	10	20	30	95	170
pH (standard units)	63	6.5	5.5	6.0	6.2	6.5	6.9	7.4	7.4	288	7.5	5.4	6.8	7.3	7.5	7.8	8.1	8.8	178	6.5	4.5	5.6	6.1	6.5	6.8	7.6	8.4	480	6.5	5.0	5.6	6.1	6.4	6.8	7.5	9.0	51	6.6	5.5	5.9	6.1	6.5	6.9	7.7	8.2
Specific cond. (µS/cm at 25°C)	63	112	30	37	50	80	117	279	920	288	357	14	107	250	340	450	650	850	178	113	10	33	60	90	130	264	700	480	104	9	23	49	75	138	275	990	51	82	10	24	40	54	118	185	268
Aluminum (ppb)	60	41	3	11	15	21	43	140	158	284	49	4	10	20	34	59	146	434	171	51	4	12	16	22	42	121	1182	468	45	3	11	16	23	46	149	328	51	48	3	12	20	25	43	170	278
Chloride (ppm)	57	7	2	3	4	5	8	12	26	263	9	2	3	4	6	10	25	74	160	10	3	4	5	7	11	25	63	458	9	1	4	5	6	10	22	163	47	7	2	3	4	5	6	15	33
Fluoride (ppb)	32	75	15	16	28	42	57	273	487	159	184	10	15	32	70	183	550	3154	73	79	1	15	30	52	83	263	726	234	65	9	14	28	48	71	151	663	36	254	15	18	41	61	128	1628	2065
Manganese (ppb)	49	54	2	5	13	34	80	134	473	116	105	4	8	36	89	154	225	792	138	49	0	5	14	28	53	153	575	387	46	0	4	12	32	57	128	680	37	29	3	5	10	20	40	74	159
Sodium (ppm)	54	6.4	1.1	1.4	2.6	4.8	9.9	15.4	17.0	247	6.0	0.1	0.6	1.4	2.8	7.2	21.7	95	155	7.5	0.1	1.9	3.9	5.1	9.4	19	61	435	7	0.2	1.3	2.9	4.9	9.8	18.7	54.8	45	5.8	0.4	1.9	3.1	4.6	6.6	13.4	20
Uranium (ppb)	63	0.21	0.00	0.00	0.01	0.04	0.13	0.94	2.9	288	0.35	0.00	0.02	0.08	0.17	0.31	1.4	5.3	178	1.63	0.00	0.00	0.02	0.05	0.12	0.8	259	480	0.18	0.00	0.00	0.01	0.03	0.07	0.45	9.8	51	0.04	0.00	0.00	0.01	0.02	0.03	0.20	0.24

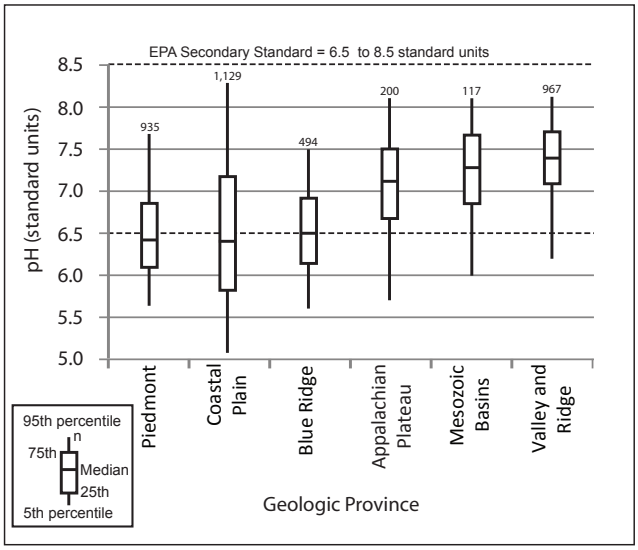
Property or Constituent	Gravel									Limestone									Metasedimentary Rocks									Metavolcanic Rocks									Mylonite								
	n	Mean	Percentile values							n	Mean	Percentile values							n	Mean	Percentile values							n	Mean	Percentile values							n	Mean	Percentile values						
			Min.	5%	25%	50%	75%	95%	Max.			Min.	5%	25%	50%	75%	95%	Max.			Min.	5%	25%	50%	75%	95%	Max.			Min.	5%	25%	50%	75%	95%	Max.			Min.	5%	25%	50%	75%	95%	Max.
Total Depth (ft)	276	401	58	120	280	363	506	778	1005	50	367	124	173	243	361	460	644	791	283	334	62	121	243	307	400	600	1000	108	356	79	161	270	320	427	609	680	33	411	58	199	300	350	520	604	1013
Casing Depth (ft)	236	285	32	59	198	279	375	542	995	37	120	18	50	65	100	133	281	395	235	73	23	50	54	63	86	122	254	95	75	30	50	55	63	81	129	252	30	66	48	50	51	55	69	117	130
Yield (gpm)	286	148	2	10	30	57	116	410	2118	54	71	3	6	20	40	90	172	700	289	30	1	4	10	18	35	100	275	114	42	2	3	14	24	45	137	350	33	21	2	2	5	8	27	77	95
pH (standard units)	542	6.2	4.2	5.0	5.6	6.1	6.7	8.1	8.8	109	7.5	5.3	7.0	7.3	7.4	7.6	8.0	9.5	190	6.4	4.9	5.6	6.0	6.4	6.8	7.3	9.9	192	6.7	5.1	5.7	6.2	6.6	7.1	7.8	9.2	59	6.8	5.2	5.8	6.3	6.7	7.2	8.1	8.9
Specific cond. (µS/cm at 25°C)	542	182	20	40	80	140	250	469	1200	109	431	16	146	305	390	500	700	3420	190	91	15	20	38	66	120	256	480	192	142	20	33	65	100	156	398	998	59	103	20	39	59	82	129	210	400
Aluminum (ppb)	538	218	9	22	77	128	196	781	3825	108	76	8	10	21	36	86	163	1997	186	46	2	10	16	27	44	161	318	188	42	3	10	14	20	35	140	599	57	42	10	11	17	28	42	131	160
Chloride (ppm)	526	14	2	4	6	10	17	35	191	93	13	3	3	5	7	13	39	100	174	8	1	4	5	5	8	22	74	179	11	3	4	5	8	13	31	42	57	9	3	4	5	6	11	24	32
Fluoride (ppb)	267	296	9	16	28	56	158	1707	4458	61	225	11	17	35	76	185	791	4548	81	43	8	11	18	32	51	108	273	70	89	7	13	20	42	66	297	1279	29	83	10	12	51	59	106	194	256
Manganese (ppb)	504	76	2	14	42	63	83	142	3911	58	129	8	17	51	96	167	288	917	160	49	1	5	15	39	61	136	389	143	52	2	5	15	31	63	144	620	43	47	2	4	15	39	60	136	227
Sodium (ppm)	518	21.1	0.2	2.8	9.1	13.2	19	70.0	220	93	19.4	0.2	0.7	2.1	4.8	10.9	36.0	707.6	165	5.7	0.3	1.2	2.4	3.6	6.0	16.0	36.7	174	7.6	0.6	2.1	4.0	5.6	9.4	18	35	54	7.0	1.0	2.0	3.2	5.5	7.4	17.5	21.8
Uranium (ppb)	543	0.09	0.00	0.00	0.01	0.03	0.06	0.29	5.9	109	0.39	0.00	0.02	0.08	0.17	0.42	1.5	4.4	190	0.07	0.00	0.00	0.00	0.03	0.05	0.23	2.5	192	0.09	0.00	0.00	0.02	0.04	0.08	0.38	1.6	59	12.70	0.00	0.00	0.02	0.04	0.10	0.78	729

Property or Constituent	Sand									Sandstone									Schist									Shale								
	n	Mean	Percentile values							n	Mean	Percentile values							n	Mean	Percentile values							n	Mean	Percentile values						
			Min.	5%	25%	50%	75%	95%	Max.			Min.	5%	25%	50%	75%	95%	Max.			Min.	5%	25%	50%	75%	95%	Max.			Min.	5%	25%	50%	75%	95%	Max.
Total Depth (ft)	461	402	53	90	242	370	561	787	1077	63	372	63	114	220	352	500	721	1003	85	301	60	100	205	300	380	500	750	174	356	55	136	222	320	440	706	1050
Casing Depth (ft)	415	291	21	53	157	270	392	617	960	50	70	14	50	51	60	97	121	140	74	69	27	50	54	62	82	104	122	156	93	26	50	53	63	104	237	580
Yield (gpm)	475	160	3	13	40	63	157	489	2200	69	41	1	2	10	25	50	118	320	88	29	3	4	10	21	34	75	175	179	68	2	6	24	45	82	200	500
pH (standard units)	572	6.8	4.3	5.2	6.0	6.7	7.6	8.4	8.9	208	7.0	4.3	5.7	6.6	7.1	7.5	7.9	8.5	171	6.5	5.1	5.6	6.0	6.4	6.8	7.7	8.9	653	7.3	3.7	6.1	7.0	7.3	7.7	8.1	9.8
Specific cond. (µS/cm at 25°C)	572	277	20	60	120	220	350	604	1900	208	214	10	39	100	185	283	487	1000	171	103	5	20	40	70	128	308	890	653	262	10	69	156	230	333	564	1150
Aluminum (ppb)	562	167	8	28	77	117	183	437	3346	203	64	8	11	26	45	83	160	441	164	43	3	11	16	21	44	145	212	646	59	3	11	26	43	69	139	1466
Chloride (ppm)	556	21	1	3	6	12	20	65	333	197	9	2	3	4	6	10	27	63	160	10	3	4	5	6	10	28	65	622	9	1	3	4	5	9	23	191
Fluoride (ppb)	339	511	9	17	38	100	509	2621	5746	131	115	13	17	33	56	100	305	2838	74	63	7	14	35	55	77	147	322	463	95	2	18	38	67	104	248	1218
Manganese (ppb)	527	82	3	21	49	69	97	191	569	155	163	3	13	56	106	198	530	1042	136	72	1	5	15	38	79	204	1406	480	172	2	16	56	117	198	460	3798
Sodium (ppm)	554	32.6	0.7	3.7	9.5	14.4	35.3	138.0	263.0	195	9.8	0.5	1.5	3.7	7.3	11	27.6	87	154	7.8	0.6	1.2	2.9	5.0	11.3	18.9	55.8	613	11.7	0.1	1.0	3.4	7.2	14.2	38.5	130
Uranium (ppb)	572	0.07	0.00	0.00	0.00	0.01	0.04	0.17	15.4	208	0.34	0.00	0.00	0.01	0.03	0.13	1.4	16.0	171	0.13	0.00	0.00	0.02	0.03	0.06	0.37	6.1	654	0.20	0.00	0.00	0.01	0.04	0.13	0.94	14.8

Table 2. Statistical summary of public supply well records (Virginia Department of Health, unpublished data) and NURE well water analyses (Smith, 1997) by major rock type.

less than two percent of all well water samples in the NURE dataset would have exceeded the EPA standard for TDS.

Specific conductance varies by province (Figure 7, Table 1). The Valley and Ridge Province has the highest interquartile range. The Coastal Plain, Appalachian Plateau, and Mesozoic Basins have intermediate ranges, and the Piedmont and Blue Ridge have the lowest ranges. Water samples from wells assigned to metamorphic rocks and felsic plutons have the lowest ranges of specific conductance and show the less variability (Figure 7, Table 2). Water samples from wells assigned to sedimentary rocks have higher ranges and show more variability (Figure 7, Table 2).



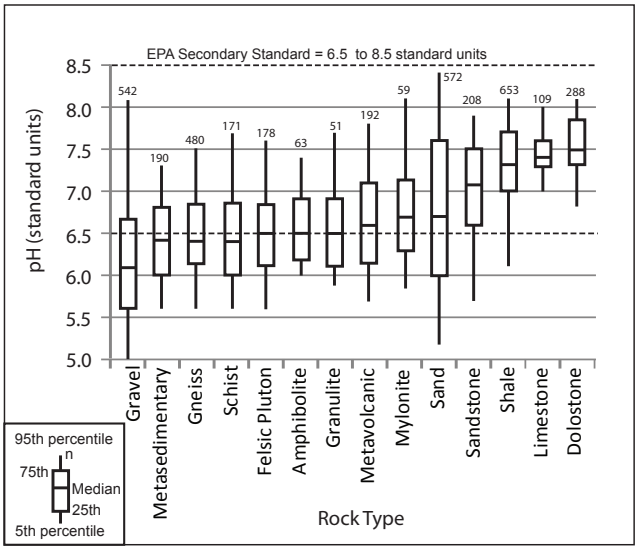
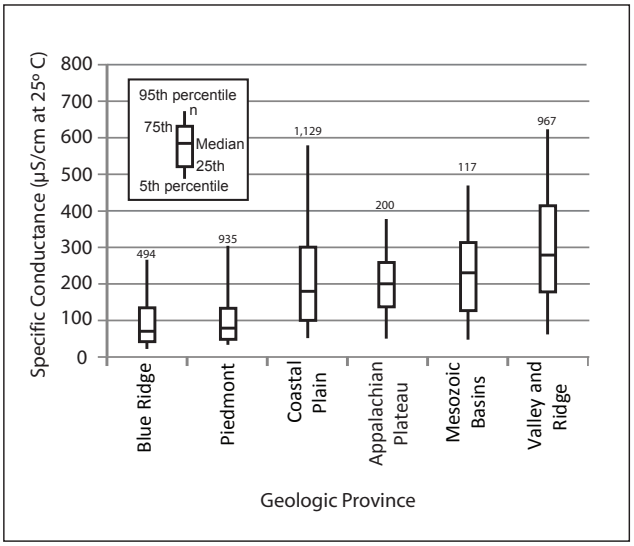


Figure 6. Variation in pH by geologic province and major rock type. Dashed lines indicate upper and lower levels of pH that meet EPA secondary limits.



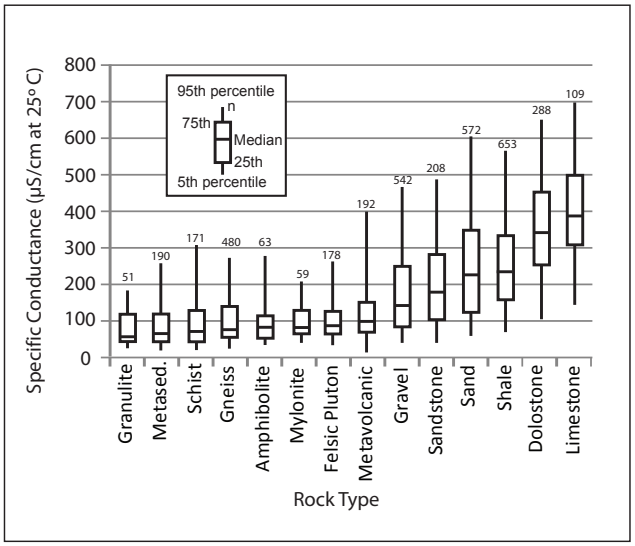


Figure 7. Variation in specific conductance by geologic province and major rock type.

Aluminum

The NURE dataset contains 3,770 aluminum analyses. Aluminum is a naturally occurring element and is added to some water systems as a component of alum to remove dissolved solids. The EPA recommends that aluminum concentrations in drinking water not exceed 0.05 to 0.2 mg/L, which is equivalent to 50 to 200 parts per billion (ppb) (U.S. EPA, 2007). The U.S. Food and Drug Administration (FDA) has a recommended level for aluminum concentrations in bottled water of 0.2 mg/L, which is equivalent to 200 ppb (U.S. FDA, 2007). These limits are based on aesthetic qualities, related to color. A relationship between elevated aluminum concentrations in drinking

water and the incidence of Alzheimer's disease may also exist (Rondeau and others, 2000).

Aluminum concentrations in approximately 47 percent of the water samples in the NURE dataset exceed 50 ppb. Approximately 8 percent of the water samples had concentrations that exceeded 200 ppb; 85 percent of these samples are from wells located in the Coastal Plain Province. The highest aluminum concentration in the dataset is 3,825 ppb, also from a well in the Coastal Plain. Aluminum concentrations vary by province, with higher levels being most common in the Coastal Plain (Table 1). Concentrations also vary by rock type, with water samples from wells in crystalline rocks of the Blue Ridge and Piedmont having the lowest concentration levels (Figure 8, Table 2). Water from wells in areas that are underlain by sedimentary rocks of the Appalachian Plateau, Valley and Ridge and Mesozoic Basins have slightly higher of levels of aluminum, and wells in unconsolidated sand and gravel formations have the highest levels of aluminum, with nearly 75 percent of water samples from wells in these formations exceeding 50 ppb.

Chloride and Sodium

The NURE dataset contains 3,633 chloride analyses and 3,537 sodium analyses. Sodium and chloride occur naturally in ground water and are also used in water softeners to reduce hardness and improve water quality. Elevated levels of sodium and chloride in untreated water generally indicate increased salt content. The EPA recommends that chloride in drinking water not exceed concentrations of 250 mg/L, which is equivalent to 250 parts per million (ppm), for taste purposes (U.S. EPA, 2007). Only six wells, all of which are in the Coastal Plain, had water samples with chloride concentrations above 250 ppm.

EPA has established a Drinking Water Equivalent Level of 20 mg/l for sodium, which is equivalent to 20 ppm (U.S. EPA, 2006). This level is a non-enforceable guidance level that applies to individuals on a 500 mg/day sodium restricted diet. Fourteen percent of water samples in the NURE dataset contained more than 20 ppm of sodium (Table 1). Two thirds of these samples were from wells from the Coastal Plain province.

Water samples from wells in areas underlain by unconsolidated sand and gravel formations have the highest concentration ranges of chloride and sodium. Water samples from some wells drilled in some sedimentary and volcanic rock formations have slightly higher chloride concentrations. Samples from wells in most other rock types are low in sodium and chloride (Figure 8, Table 2).

Fluoride

The NURE dataset contains 2,095 fluoride analyses. Fluoride is naturally occurring and is added to some water systems to improve dental health. Excessive fluoride levels may cause health problems. As a result, the EPA has established an enforceable drinking water standard of 4.0 mg/l, which is equivalent to 4,000 ppb, for fluoride in public water supplies (U.S. EPA, 2007) and a secondary standard of 2.0 mg/l, which is equivalent to 2,000 ppb, related to the aesthetic effect of tooth discoloration (U.S. EPA, 2006). The FDA has a temperature dependent limit for fluoride that is as low as 1.4 mg/l (U.S. FDA, 2007), which is equivalent to 1,400 ppb, for bottled water and other beverages. Approximately three percent of water samples in the dataset have fluoride concentrations that exceed the most stringent FDA standard. Approximately two percent of water samples in the dataset exceeded the secondary EPA standard. Only nine samples exceeded EPA's enforceable drinking water standard. Fluoride concentrations are generally low, with elevated concentrations being most common in water samples from wells in the Coastal Plain and Valley and Ridge provinces, and the Mesozoic Basins (Table 1). Water samples from wells assigned to unconsolidated sand formations have the highest range of concentrations (Figure 8; Table 2).

Manganese

The NURE dataset contains 2,998 manganese analyses. Elevated manganese can cause aesthetic problems related to color, staining, and taste. As a result, the EPA has established a secondary limit of 0.05 mg/l, which is equivalent to 50 ppb (U.S. EPA, 2007). The FDA uses the same standard for bottled water (U.S. FDA, 2007). Approximately 58 percent of the wells tested in the NURE dataset had manganese concentrations above 50 ppb and exceed this secondary limit. Manganese concentrations have the highest values and range in the Appalachian Plateau province (Table 1) and the lowest ranges in the Blue Ridge and Piedmont provinces. Water samples from wells in limestone, dolostone, sandstone, and shale rock types have the highest ranges of manganese concentrations (Figure 8; Table 2).

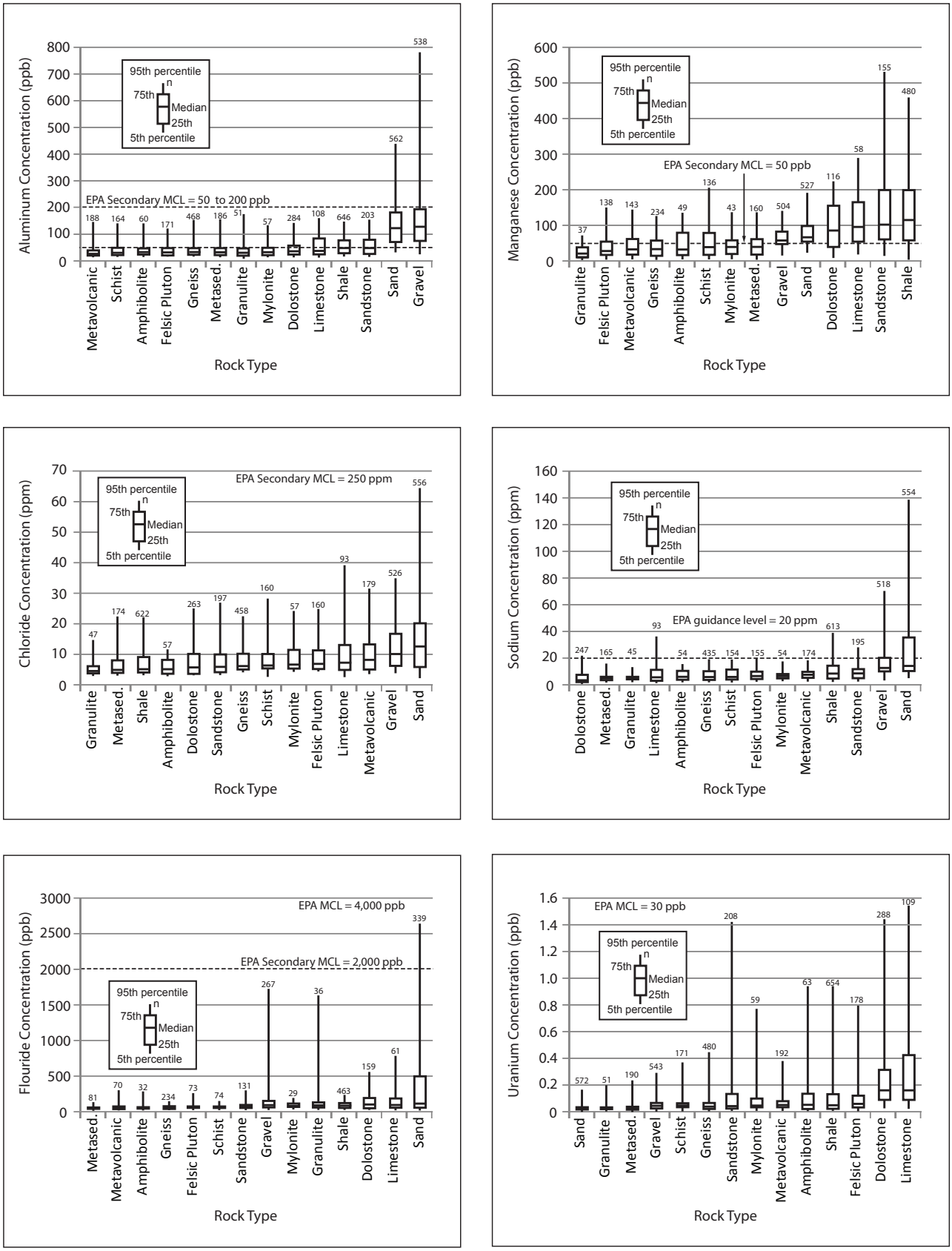


Figure 8. Variation of water quality parameters in Virginia by major rock type. Dashed lines indicate EPA maximum contaminant level (MCL) or guidance level.

Uranium

The NURE dataset contains 3,844 uranium analyses. Uranium can pose health risks at elevated concentrations. As a result, the EPA has established a maximum level for uranium of 30 micrograms per liter (µg/l), which is equivalent to 30 ppb (U.S. EPA, 2007). Uranium was less than the detection limit of 0.01 ppb in 17 percent of the samples. 96 percent of samples were less than 1 ppb. Only two water samples exceeded the EPA limit. Both of these samples are from wells assigned to the Piedmont province. One well is assigned to a felsic pluton rock type and produced a water sample that contained 259 ppb of uranium. The other well is assigned to a mylonite map unit and produced a water sample that contained 729 ppb of uranium. Slightly elevated levels of uranium, which are an order of magnitude below the EPA standard, are somewhat common in water from wells in areas underlain by limestone, dolostone, sandstone, amphibolite, shale, and felsic pluton rock types (Figure 8; Table 2).

DISCUSSION

A number of regional and local groundwater studies have been completed in Virginia. A partial listing of related publications is presented in Table 3 and in a selected bibliography. A review of these publications indicates that the data presented here is generally consistent with previous findings. The Virginia Department of Environmental Quality, Office of Ground Water Characterization is currently compiling existing water well data in Virginia from a number of sources. This dataset, when complete, should contain more than ten times the number of wells considered in this report and a broader suite of analytical data. The following general statements may be made based on the analysis of public well and NURE datasets in this report:

- Well depth is variable within every geologic province and major rock type (many wells are drilled to locally known aquifer depths in the Coastal Plain province);
- Wells drilled into limestone and dolostone will typically require more casing than other wells (about 50 percent will need more than 100 feet of casing);
- About 75 percent of wells installed into non-carbonate bedrock (west of the Coastal Plain) will require less than 90 feet of casing;
- High yielding public supply wells (>100 GPM) are present in all geologic provinces;
- High yielding public supply wells (>100 GPM) are least common (about 1 well in 20) in the Appalachian Plateau, Piedmont and Blue Ridge provinces;
- High yielding public supply wells (>100GPM) are most common (about 1 well in 3) in the Coastal Plain province;
- Larger diameter drilled wells will typically have higher well yields;
- Water quality parameters in the Coastal Plain are more variable than in other provinces;
- Water quality parameters in the Blue Ridge and Piedmont are less variable than in other provinces;
- Low pH is a common problem in the Blue Ridge, Coastal Plain, and Piedmont Provinces;
- Aluminum concentrations that exceed the most stringent secondary drinking water standards may occur in water from wells in all rock types; elevated levels are most common in water from wells in sedimentary rock types and unconsolidated sediments;
- Fluoride concentrations that exceed drinking water standards are uncommon outside of the Coastal Plain province; in the Coastal Plain province, about 1 well in 20 may exceed the secondary drinking water standard of 2 mg/L and about 1 well in 100 may exceed the primary drinking water standard of 4 mg/L;
- Manganese concentrations that exceed secondary drinking water standards are less common (about 1 well in 3 or 4) in water samples from wells drilled in metamorphic and igneous rock types and more common (about 3 wells in 4) in water samples from wells assigned to sedimentary rock types and unconsolidated sediments;
- Concentrations of chloride that exceed drinking water standards are rare in Virginia;
- Elevated levels of uranium in well water are not common in Virginia, but a very small percentage of wells may have uranium at very high levels.

Table 3. A partial listing of ground-water studies relating to Virginia.

County studies

Accomack
Sinnott and Tibbitts (1968)
Albemarle
Cross (1960)
Sterrett and Hinkle (1980)
Augusta
Hinkle and Sterrett (1978)
Botetourt
Breeding and Dawson (1976b)
Buchanan
Epps (1978)
Clarke
Hubbard (1990)
Wright (1990)
Dickenson
Dovel (1983)
Fairfax
Johnston and Larson (1979)
Zenone and Larson (1983)
Franklin
Brown and Cosner (1974)
Fluvanna
Evans and Hostettler (2001)
Frederick
Harlow and others (2005)
Halifax
LeGrand (1960)
Hanover
Ellison and Masiello (1979)
Henrico
Wigglesworth and others (1984)
Henry
Dawson and Davidson (1979)
James City
Harsh (1980)
Loudon
Murphy (1979)
Sutphin and others (2000)
Northampton
Sinnott and Tibbitts (1968)
Pittsylvania
LeGrand (1960)

County studies (cont'd)

Prince William
Comer (1976)
Nelms and Brockman (1997)
Roanoke
Breeding and Dawson (1976a)
Rockbridge
Van der Leeden (2004)
Rockingham
Hinkle and Sterrett (1976)
Shenandoah
Hinkle and Sterrett (1977)
Southhampton
Brown and Cosner (1974)
Spotsylvania
Subitzky (1955)
Virginia Beach, City of
Smith and Harlow (2002)
Smith (2003)
Wise
Dovel (1983)
York
Richardson and Brockman (1992)

Province studies

Appalachian Plateau
Powell and Larson (1985)
Wright (1985)
Harlow and Lecain (1993)

Blue Ridge
DeKay (1972)
Hopkins (1984)
Kozar and others (2001)

Coastal Plain
Cederstrom (1943; 1945; 1946)
DeBuchananne (1968)
Virginia Water Control Board (1970; 1973)
Newton and others (1977)
Siudyla and others (1977)

Province studies (cont'd)

Coastal Plain (cont'd)
Siudyla and others (1981)
Fennema and Newton (1982)
Knobel (1985)
Meng and Harsh (1988)
Hamilton and Larson (1988)
Meisler (1989)
Richardson and Brockman (1992)
Richardson (1994)
McFarland (1999)
Powars and Bruce (1999)
Smith (1999)
McFarland and Bruce (2007)
Pope and others (2007)

Mesozoic Basins
Laczniak and Zenone (1985)

Piedmont
LeGrand (1959)
DeBuchananne (1968)
Powell and Abe (1985)
Stanton and others (1996)

Valley and Ridge
Hall (1928)
Cady (1936)
Latta (1956)
Hack (1965)
Hollyday and Hileman (1996)
Harlow and others (2005)

Multi-province studies

Cady (1938)
Leonard (1963)
Johnston and others (1964)
Briel (1997)
Mesko and others (1999)
Nelms and others (2003)
Swain and others (2004)

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