APPENDIX M

NON-RADIOLOGICAL PARAMETERS

Appendix M

Non-Radiological Parameters

Water Quality Parameters

Introduction

Samples for various water quality parameters were collected from 44 different sources (44 data sets or samples). These sources were categorized as: hydraulic fracturing fluid, flowback water, production water, wastewater treatment influent water, and wastewater treatment effluent water.

For each category, differing numbers of samples (or data sets) were taken as follows: hydraulic fracturing fluid (three samples), flowback water (five samples), production fluid (12 samples), influent (19 samples), and effluent (five samples). All samples were of unfiltered fluids. The metals and the water quality sample results were compared to the radium gamma spectroscopy sample results to determine if a correlation existed between any water quality parameter and the corresponding radium concentration. Additional comparisons were also made between the gross alpha, gross beta, and the radium results to determine how well that data are correlated. **Table M-1** provides the metals data used for this comparison and **Table M-2** provides the water quality data used for this comparison. **Table M-3** provides the radium (Ra-226 and Ra-228) data used for this comparison.

In statistics, dependence is any statistical relationship between two random variables or two sets of data. Correlation refers to any of a broad class of statistical relationships involving dependence. In this case, the Pearson correlation was utilized. The Pearson correlation is +1 in the case of a perfect direct (increasing) linear relationship (positive correlation), −1 in the case of a perfect decreasing (inverse) linear relationship (negative correlation), and some value between −1 and 1 in all other cases, indicating the degree of linear dependence between the variables. As it approaches zero there is less of a relationship (closer to uncorrelated). The closer the coefficient is to either −1 or 1, the stronger the correlation between the variables.

All correlations were performed with both Ra-226 and Ra-228, because while they are isotopically different, they are chemically identical and should yield similar correlation results. If the correlation is not similar, this would tend to support the conjecture that the observed correlation was an anomaly.

Non-Radiological Parameters

The non-radiological water quality parameters evaluated in this study were: hardness and associated metals (Ca and Mg), pH, specific conductance and associated properties [total dissolved solids (TDS), Na, K], other metals (Ba, Fe, Mn, and Sr), and other water quality parameters (TSS and Total Chloride).

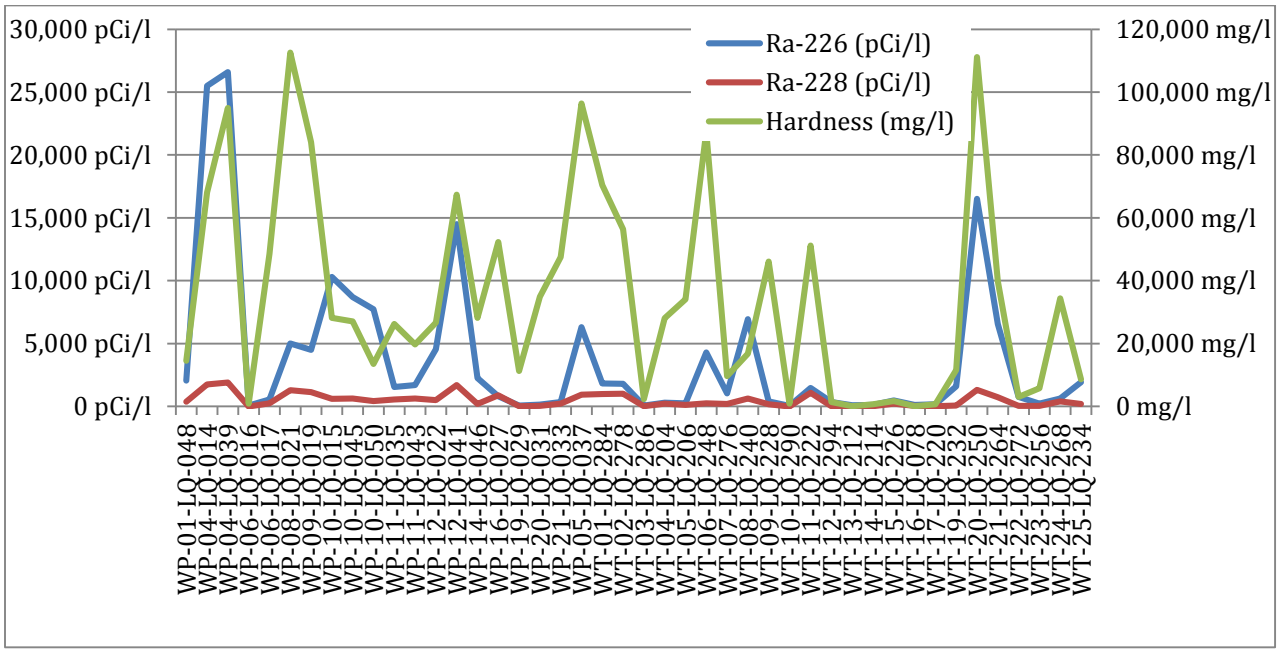
Hardness and Associated Metals (Ca and Mg)

Hardness

The simple definition of water hardness is the amount of dissolved calcium and magnesium compounds (minerals) in the water. Hard water is high in these dissolved minerals. General guidelines for classification of waters are: 0 to 60 milligrams per liter (mg/l) as soft; 61 to 120 mg/l as moderately hard; 121 to 180 mg/l as hard; and more than 180 mg/l as very hard. As can be seen in **Table M-4**, the majority of these waters would be classified as very hard.

The Pearson correlation was calculated for the total data set (44 data points) and for each of the data subsets. For much of the data, there was no significant correlation between hardness values and radium values. However, for the data sets flowback water, hydraulic fracturing fluids, influent, and effluent, there appears to be a modest correlation. However, these correlations could be an anomaly caused by the very small data set. **Figure M-1** provides a graphic depiction of the relationship between radium and hardness.

Figure M-1. Radium Concentration Verse Hardness

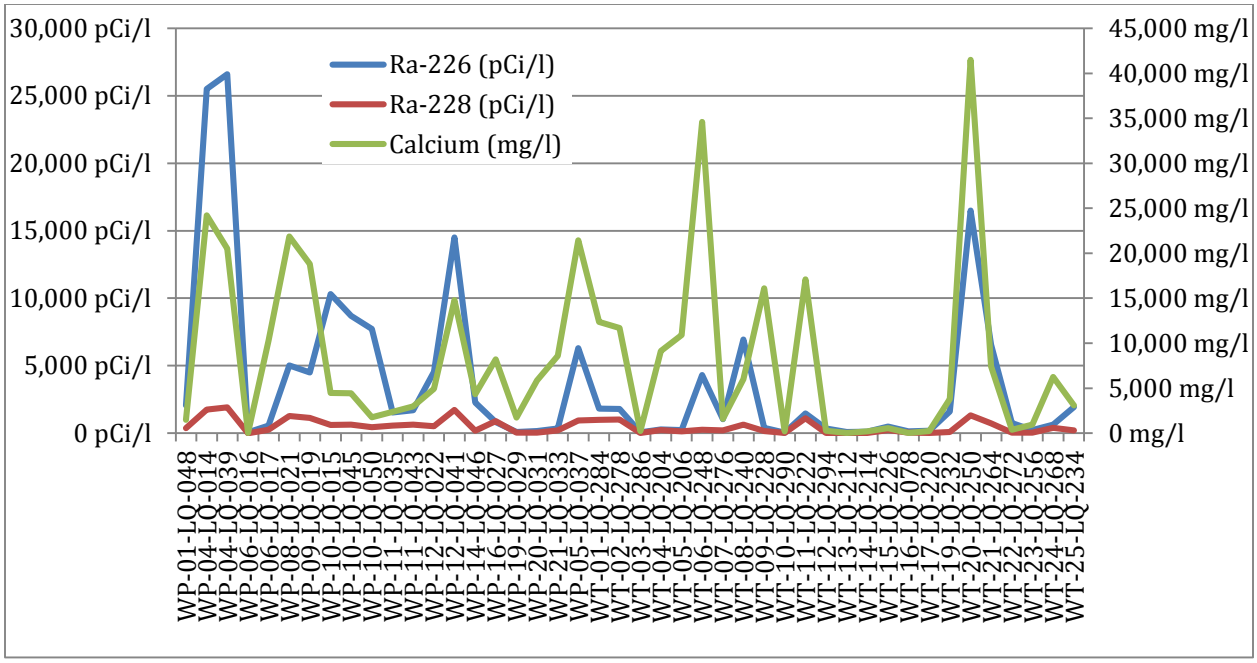


Calcium

Calcium occurs in water naturally. One of the primary reasons for the abundance of calcium in water is its natural occurrence in the earth's crust. For comparison, rivers typically contain 1-2 mg/l calcium, but in lime areas rivers may contain calcium concentrations as high as 100 mg/l. Sea water contains approximately 400 mg/l calcium.

The Pearson correlation was calculated for the total data set (44 data points) and for each of the data subsets (see **Table M-5**). For much of the data, there was no significant correlation between calcium values and radium values. However, for the data sets flowback water and influent there appears to be a modest correlation. However, these correlations could be an anomaly caused by the very small data set. **Figure M-2** provides a graphic depiction of the relationship between radium and calcium.

Figure M-2. Radium Concentration Verse Calcium

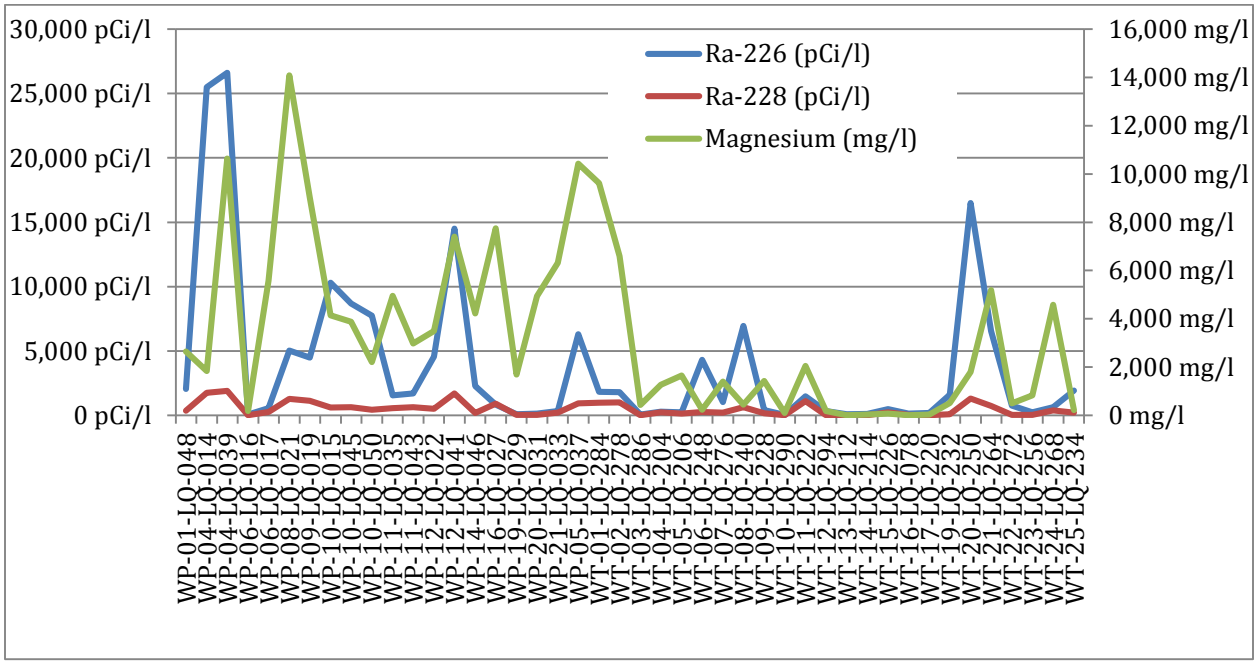


Magnesium

A large number of naturally occurring minerals contain magnesium. When magnesium is washed from these minerals and ends up in water, it, along with other alkali earth metals, causes water hardness. For comparison, magnesium is present in sea water in amounts of about 1,300 mg/l and rivers typically contain 4 mg/l of magnesium.

The Pearson correlation was calculated for the total data set (44 data points) and for each of the data subsets (see **Table M-6**). For much of the data, there was no significant correlation between magnesium values and radium values. However, for the data set, flowback water, there appears to be a modest negative correlation. The data set, hydraulic fracturing fluids, appears to show a strong positive correlation. However, these correlations could be an anomaly caused by the very small data set. **Figure M-3** provides a graphic depiction of the relationship between radium and magnesium.

Figure M-3. Radium Concentration Verse Magnesium



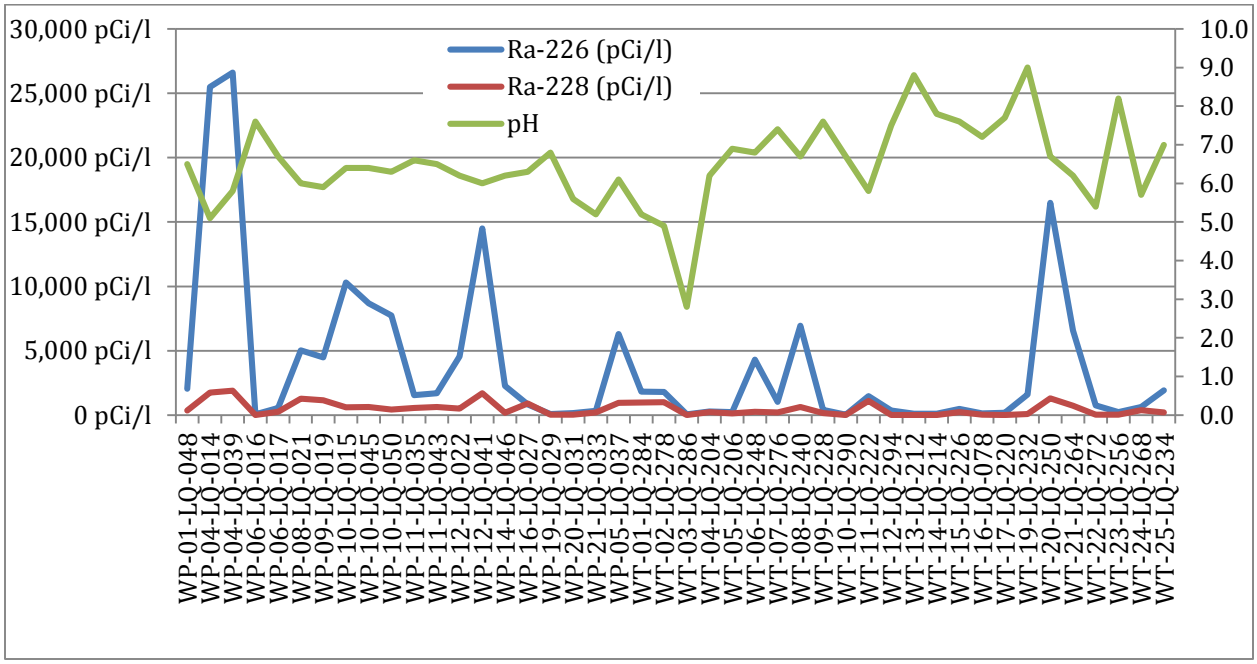
pH

pH is a measure of the relative amount of free hydrogen and hydroxyl ions in the water. Water with more free hydrogen ions is acidic (pH < 7), whereas water with more free hydroxyl ions is basic or alkaline (pH > 7). Pure water has a pH of 7.0 (neutral). For comparison, typical waste water discharge permits specify a pH range of 6.0 to 9.0 and the Resource Conservation and Recovery Act (RCRA) defines a corrosive waste as having a pH less than or equal to 2 or greater than or equal to 12.5.

None of the pH values from this study are above 9.00; however, a few values are below 6.00. Generally, the average values were in the range of 6.08 to 7.13. One data set, effluent, had a minimum pH value of 2.80 with an average of 5.26.

The Pearson correlation was calculated for the total data set (44 data points) and for each of the data subsets (see **Table M-7**). For most of the data, there was no significant correlation between pH values and radium values. One data set, flowback water, did yield a strong negative correlation with good agreement between the Ra-226 (-0.968) and Ra-228 (-0.964) values. That is, the greater the pH value, the lower the radium value. However, this result is based on only five sets of values and could easily be an anomaly caused by the very small data set. **Figure M-4** provides a graphic depiction of the relationship between radium and pH.

Figure M-4. Radium Concentration Verse pH

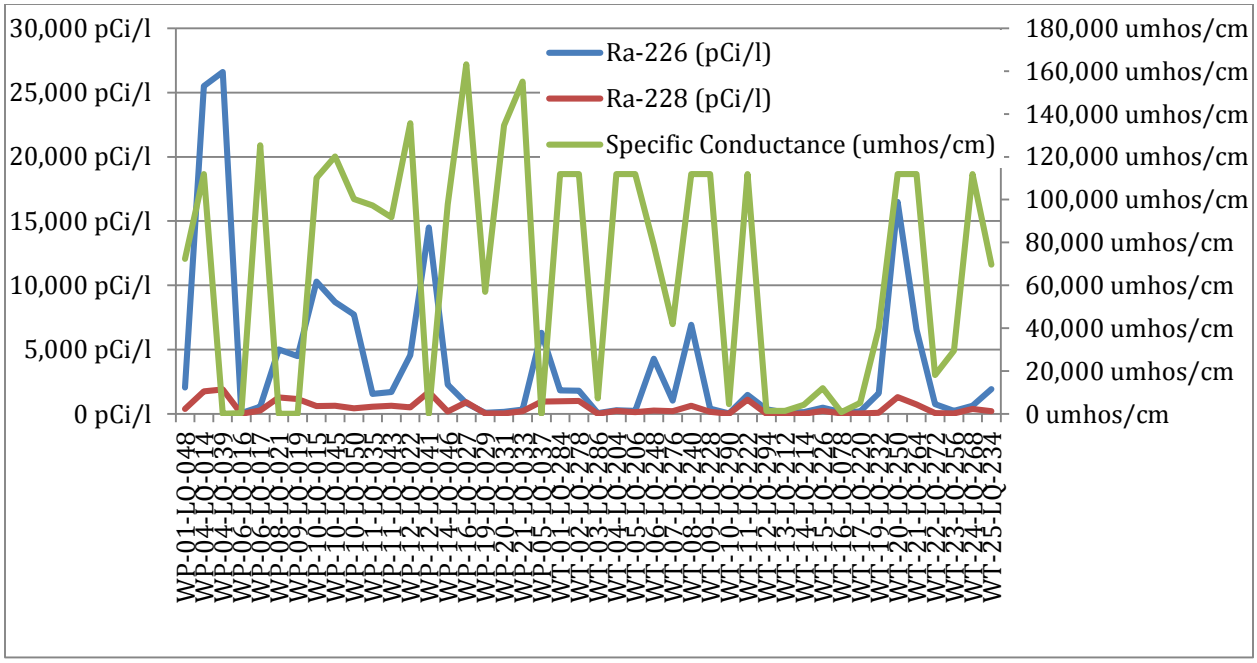


Specific Conductance and Associated Properties (TDS, Na, K)

Specific conductance is a measure of the ability of water to conduct an electrical current. It is highly dependent on the amount of dissolved solids (such as salt) in the water. Pure (distilled) water has a very low specific conductance whereas sea water (salt water) has a high specific conductance.

The Pearson correlation was calculated for the total data set (44 data points) and for each of the data subsets (see **Table M-8**). For most of the data, there was no significant correlation between specific conductance and radium values. The data sets for hydraulic fracturing fluids and effluent appear to show modest correlations with the radium results; however, these results are based on very small data sets and could easily be an anomaly. **Figure M-5** provides a graphic depiction of the relationship between radium and conductance.

Figure M-5. Radium Concentration Verse Specific Conductance

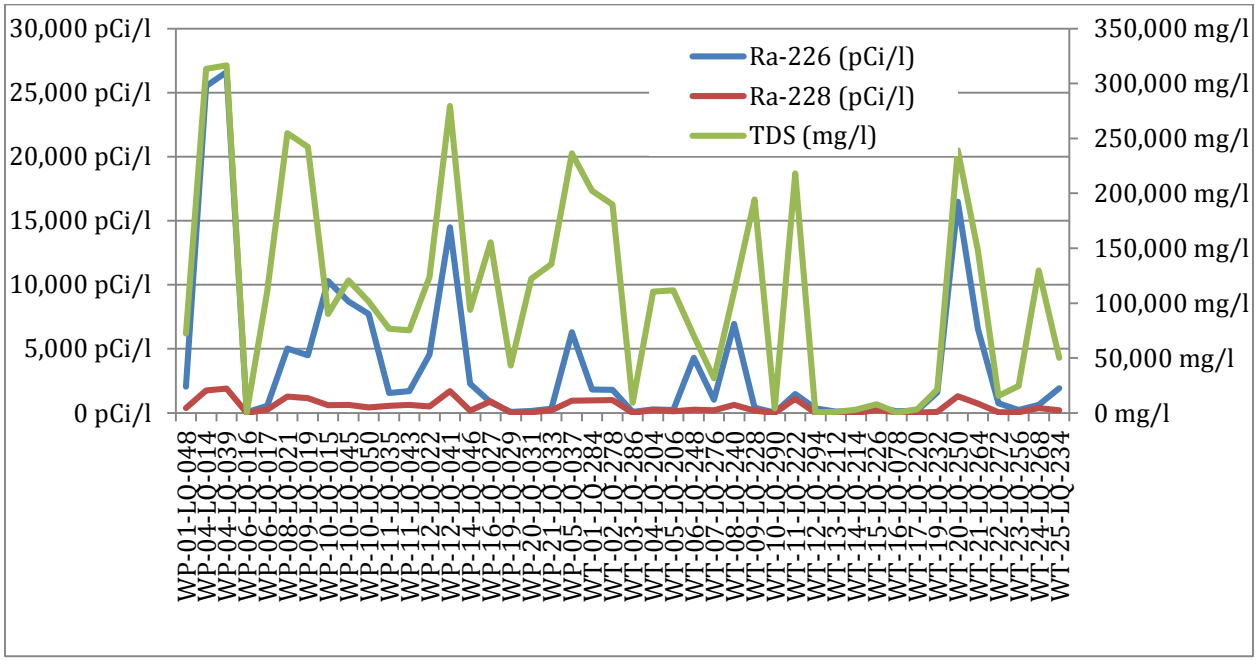


Total Dissolved Solids

TDS refer to any minerals, salts, metals, cations (positive ions), or anions (negative ions) dissolved in water.

The Pearson correlation was calculated for the total data set (44 data points) and for each of the data subsets (see **Table M-9**). The data shows no significant correlation between TDS and radium values for any of the data sets. For production fluids, there appears to be a modest correlation between the TDS values and the Ra-226 values; however, there is no corresponding correlation with the chemically identical Ra-228. **Figure M-6** provides a graphic depiction of the relationship between radium and TDS.

Figure M-6. Radium Concentration Verse Total Dissolved Solids

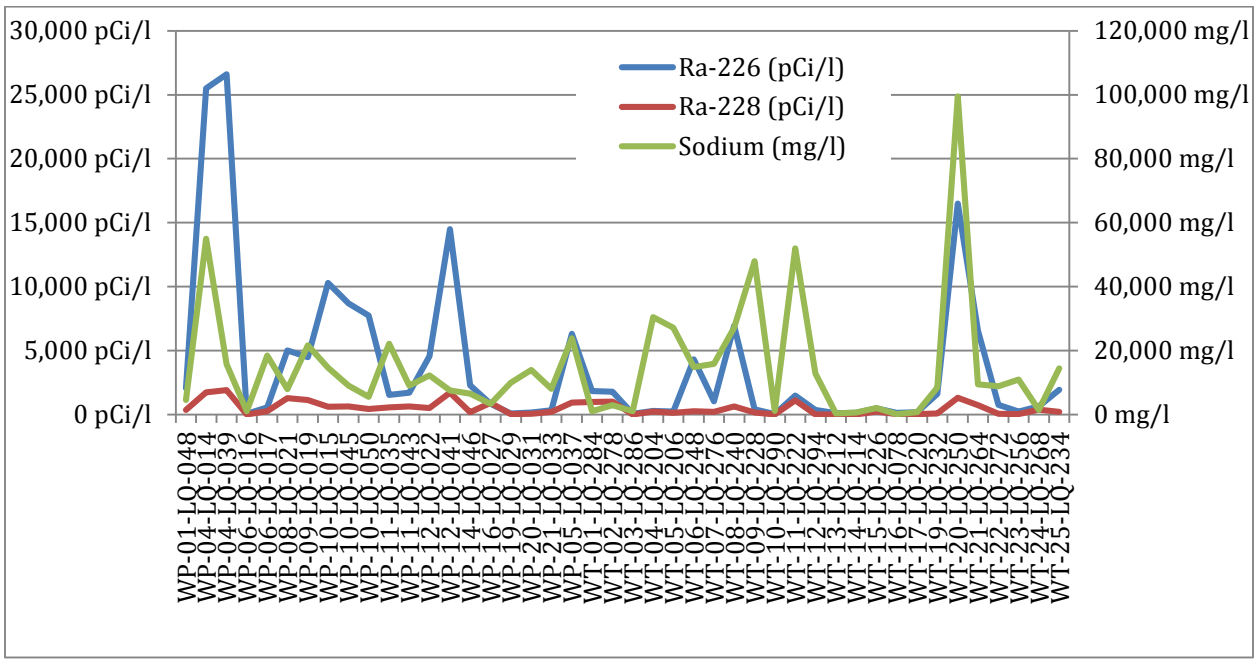


Sodium

Sodium is the most common alkali metal and the sixth most abundant element on Earth, comprising about 2.8 % of the Earth's crust. It is abundant in nature forming compounds such as salt (sodium chloride or NaCl) and comprises about 80 percent of the dissolved constituents of sea water. For comparison, drinking water contains a sodium concentration varying from 5 mg/l or less (sodium free) to 140 mg/l (low sodium). Ocean water, on average, contains approximately 35,000 mg/l.

The Pearson correlation was calculated for the total data set (44 data points) and for each of the data subsets (see **Table M-10**). For approximately half of the data, there was no significant correlation between sodium and radium values. The data sets for flowback water, hydraulic fracturing fluids, and influent appear to show modest to strong correlations with the radium results; however, these results are based on very small data sets and could easily be an anomaly. **Figure M-7** provides a graphic depiction of the relationship between radium and sodium.

Figure M-7. Radium Concentration Verse Sodium

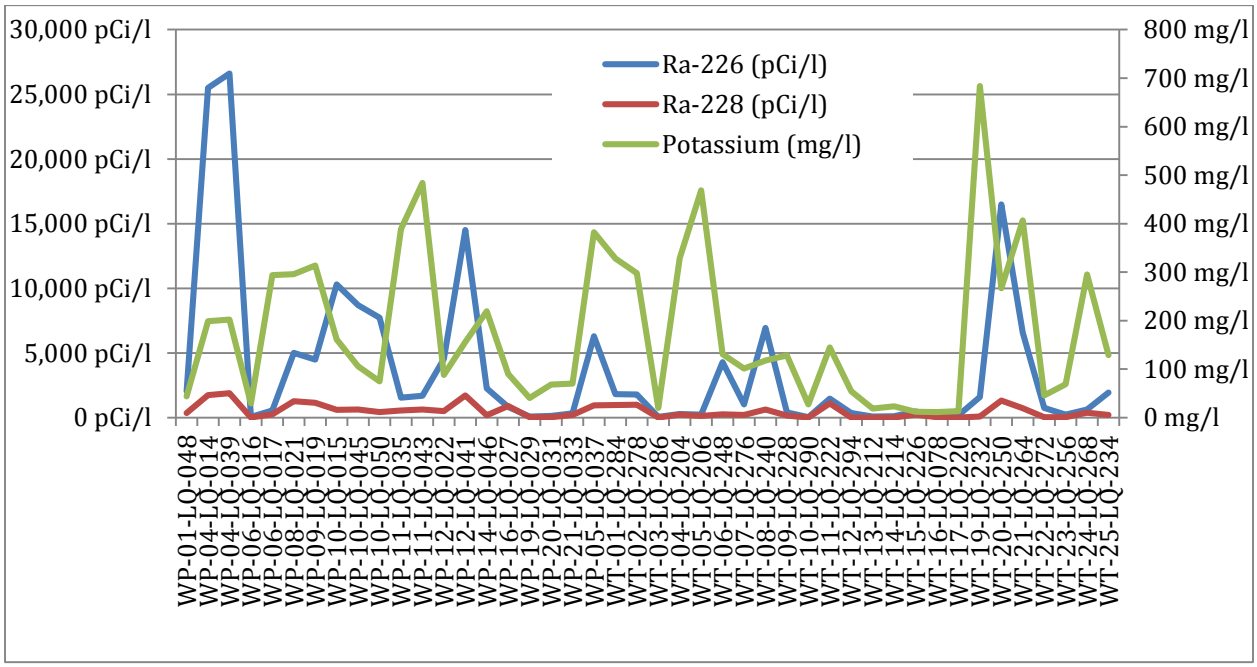


Potassium

In its various compounds, potassium makes up about 2.6% of the weight of the Earth's crust and is the seventh most abundant element. For comparison, potassium concentration in sea water is approximately 390 mg/l.

The Pearson correlation was calculated for the total data set (44 data points) and for each of the data subsets (see **Table M-11**). For most of the data, there was no significant correlation between potassium and radium values. The data set for the effluent appears to show a modest to strong correlation with the radium results; however, this result is based on very small data set and could be an anomaly. **Figure M-8** provides a graphic depiction of the relationship between radium and potassium.

Figure M-8. Radium Concentration Verse Potassium



Other Metals (Ba, Fe, Mn, and Sr)

Barium

Barium is a highly reactive alkaline earth metal not found as a free element in nature. The most common naturally occurring minerals of barium are barite (barium sulfate, $BaSO_4$) and witherite (barium carbonate, $BaCO_3$), which are both insoluble in water. For comparison, the concentration of barium in the Earth's crust is approximately 0.0425% and the concentration in ocean water is approximately 13 µg/l.

The Pearson correlation was calculated for the total data set (44 data points) and for each of the data subsets (see **Table M-12**). For most of the data, there was a significant correlation between barium and radium values. Correlations were very strong for radium and barium concentration in the effluent, influent, and hydraulic fracturing fluids. Correlations were fairly strong for radium and barium in the flowback water and for the entire data set (all 44 samples), although there was some difference in the Ra-226 and Ra-228 correlations with barium when the entire data set was compared. The correlation was weakest in the production fluid, which also expressed a difference in the Ra-226 and Ra-228 correlations with barium. **Figure M-9** provides a graphic depiction of the relationship between radium and barium. Since the relationship between barium and radium were the strongest of all of the comparisons, a linear regression was also performed. When the data was scatter plotted, a Ra-226 outlier was noticed. With the outlier included, the R^2 value was 0.662; however, with the outlier removed, the R^2 value was 0.778. **Figure M-10** provides a graphic depiction of the X-Y scatter plot of the Ra-226 versus barium with the outlier present. **Figure M-11** provides a graphic depiction of the X-Y scatter plot of the Ra-226 versus barium with the outlier removed.

Figure M-9. Radium Concentration Verse Barium

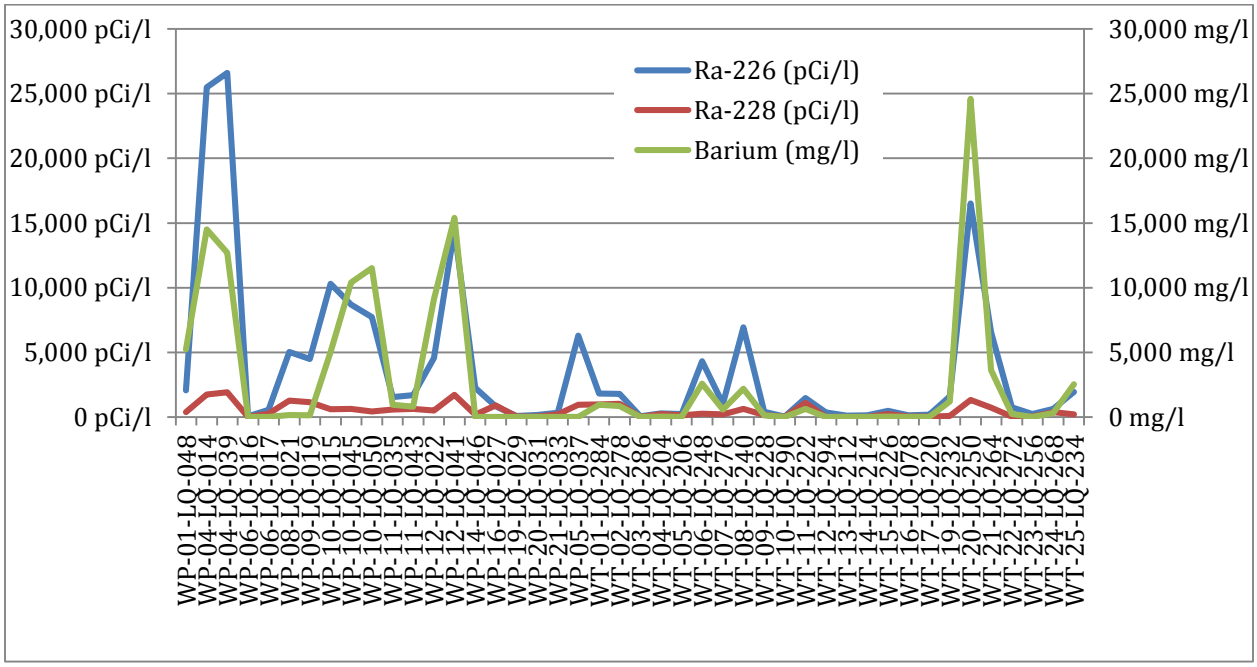


Figure M-10. Ra-226 X-Y Scatter Plot versus Barium – Outlier Present

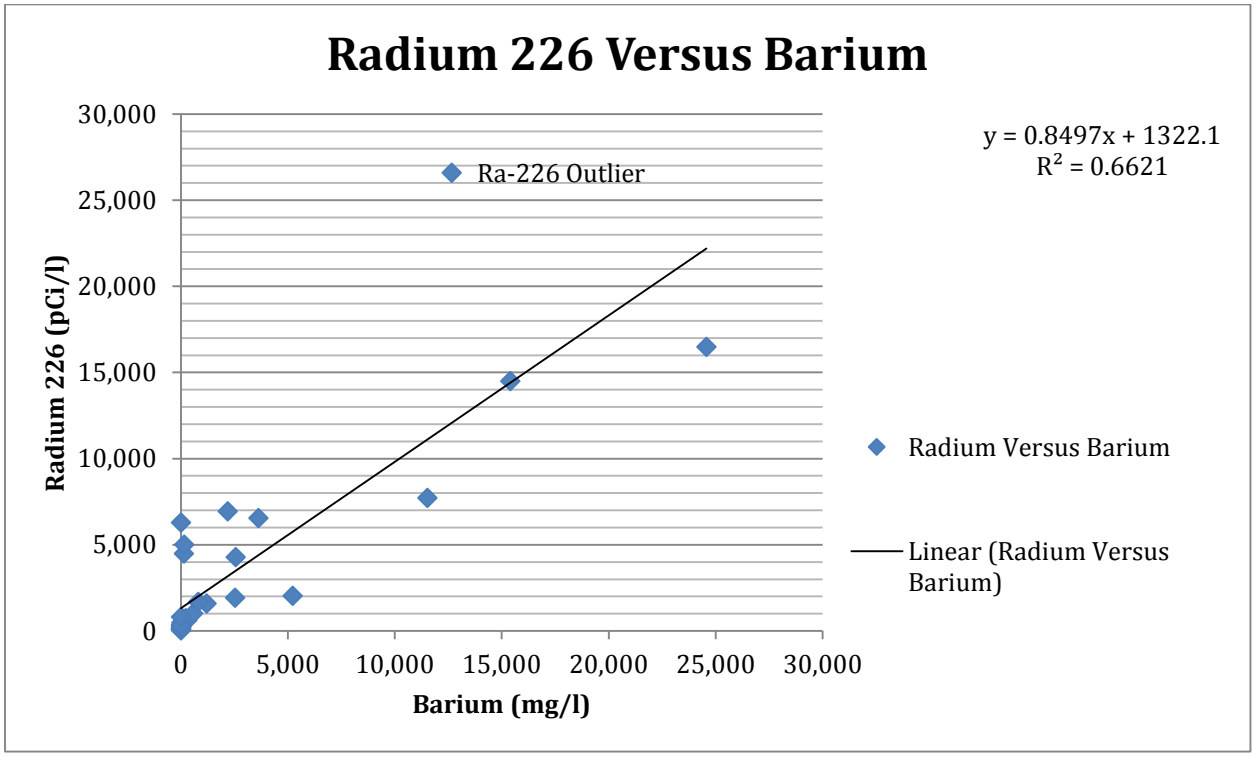
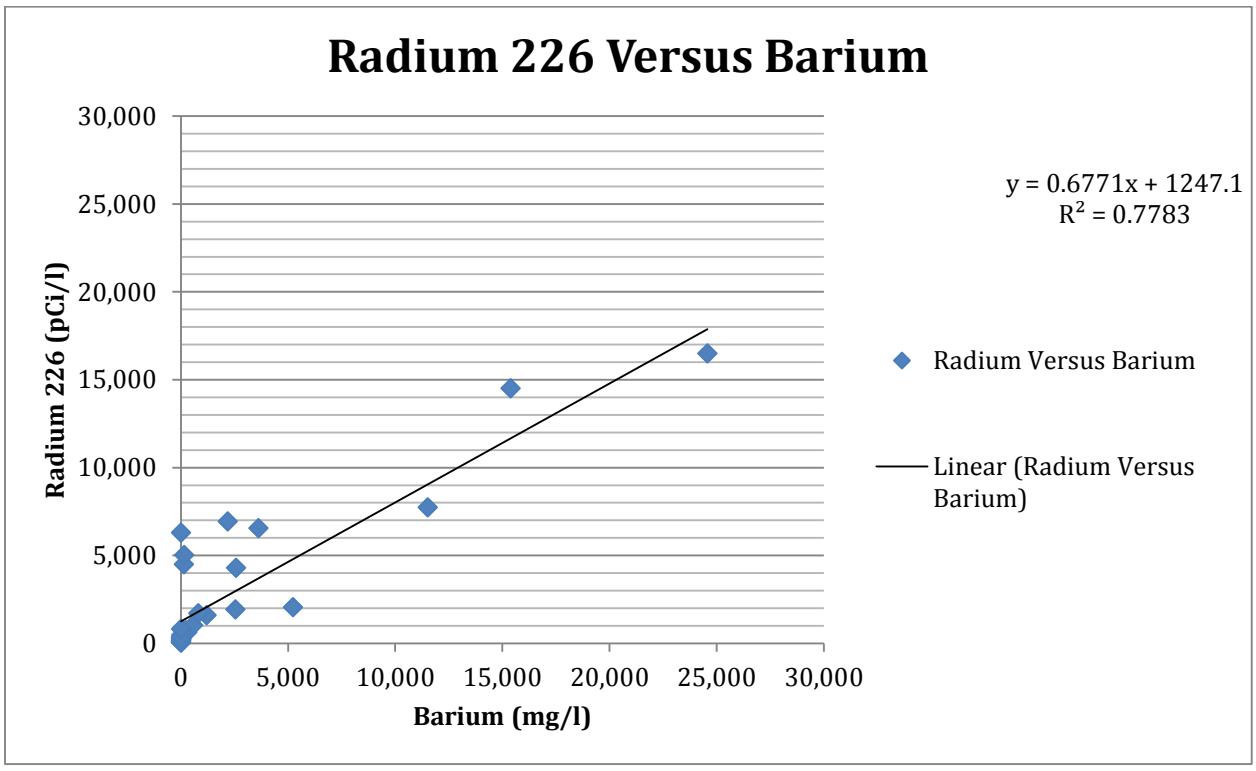


Figure M-11. Ra-226 X-Y Scatter Plot versus Barium – Outlier Removed

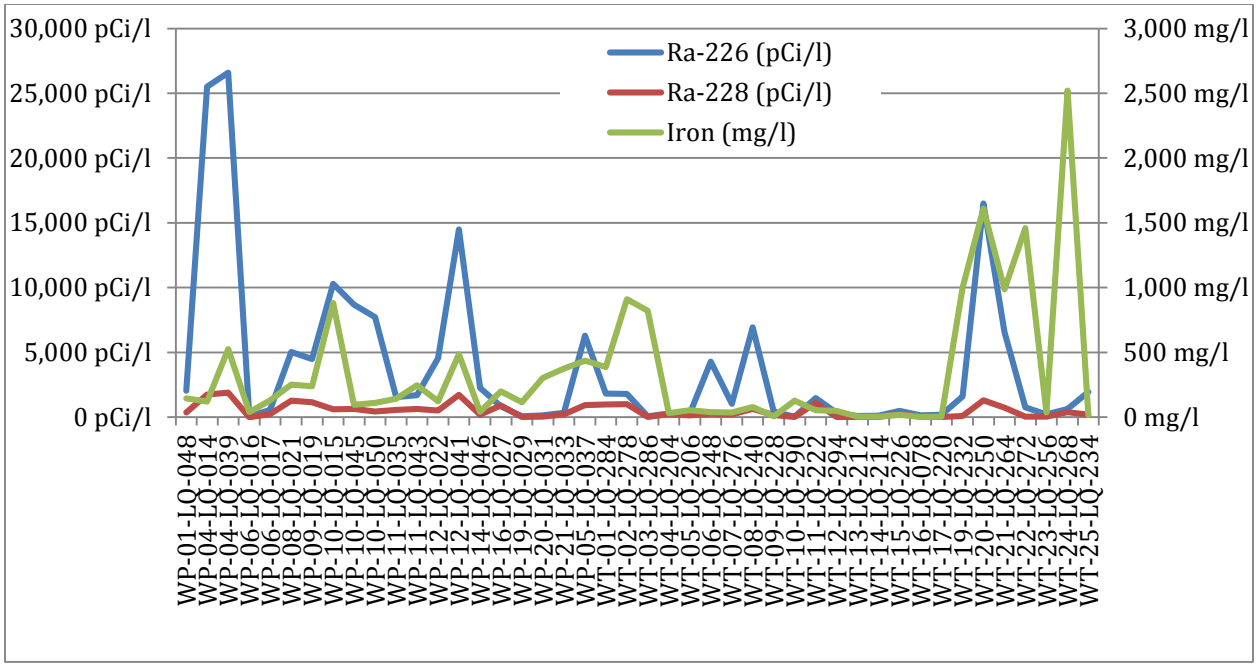


Iron

Iron is, by mass, the most common element on earth and makes up approximately 5% of the Earth's crust. Iron is biologically important, forming complexes with molecular oxygen. In groundwater, iron concentrations typically range from 0 mg/l to 50 mg/l.

The Pearson correlation was calculated for the total data set (44 data points) and for each of the data subsets (see **Table M-13**). For most of the data, there was no significant correlation between iron and radium values. The data set for the production fluid appears to show a weak correlation with the radium results and the data set for the hydraulic fracturing fluid shows a very strong correlation between the iron and radium results; however, these results are based on very small data sets and could be anomalies. **Figure M-12** provides a graphic depiction of the relationship between radium and iron.

Figure M-12. Radium Concentration Verse Iron

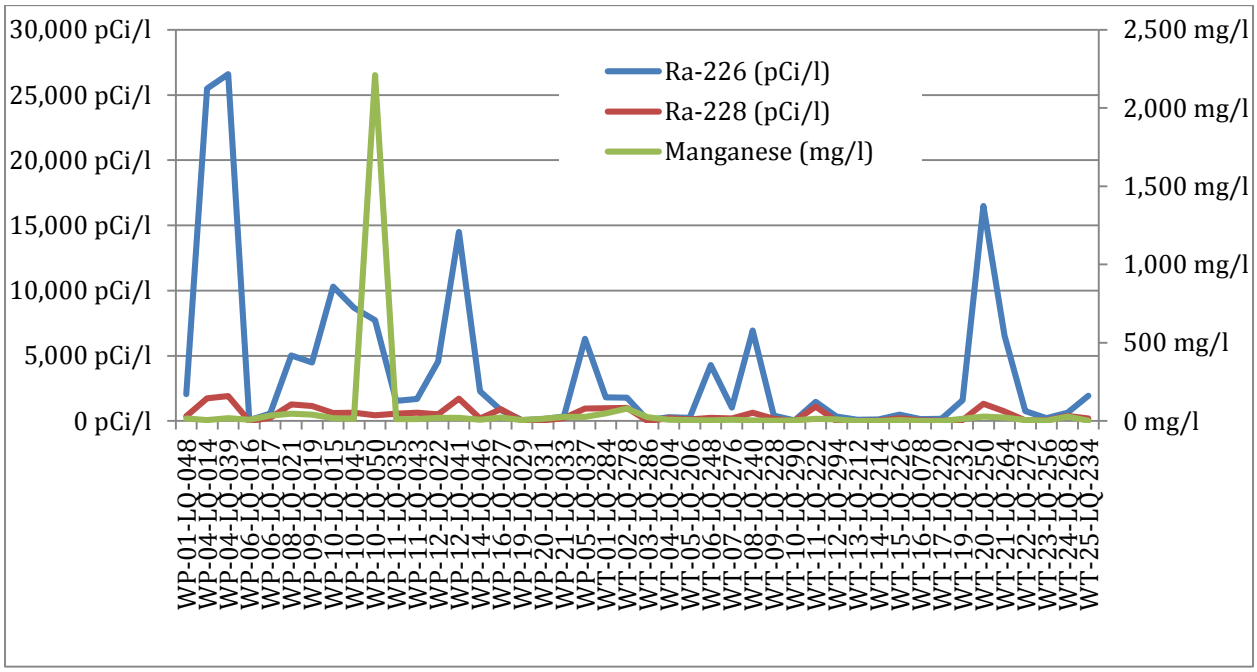


Manganese

Manganese is often found in combination with iron in nature, but is never found in elemental form. For comparison, the U.S. EPA Secondary Drinking Water Regulations recommend a limit of 0.05 mg/l manganese because of the staining that may be caused.

The Pearson correlation was calculated for the total data set (44 data points) and for each of the data subsets (see **Table M-14**). For most of the data, there was no significant correlation between manganese and radium values. The data set for the hydraulic fracturing fluid shows a very strong correlation between the manganese and radium values; however, this result is based on a very small data set and could be an anomaly. **Figure M-13** provides a graphic depiction of the relationship between radium and manganese.

Figure M-13. Radium Concentration Verse Manganese

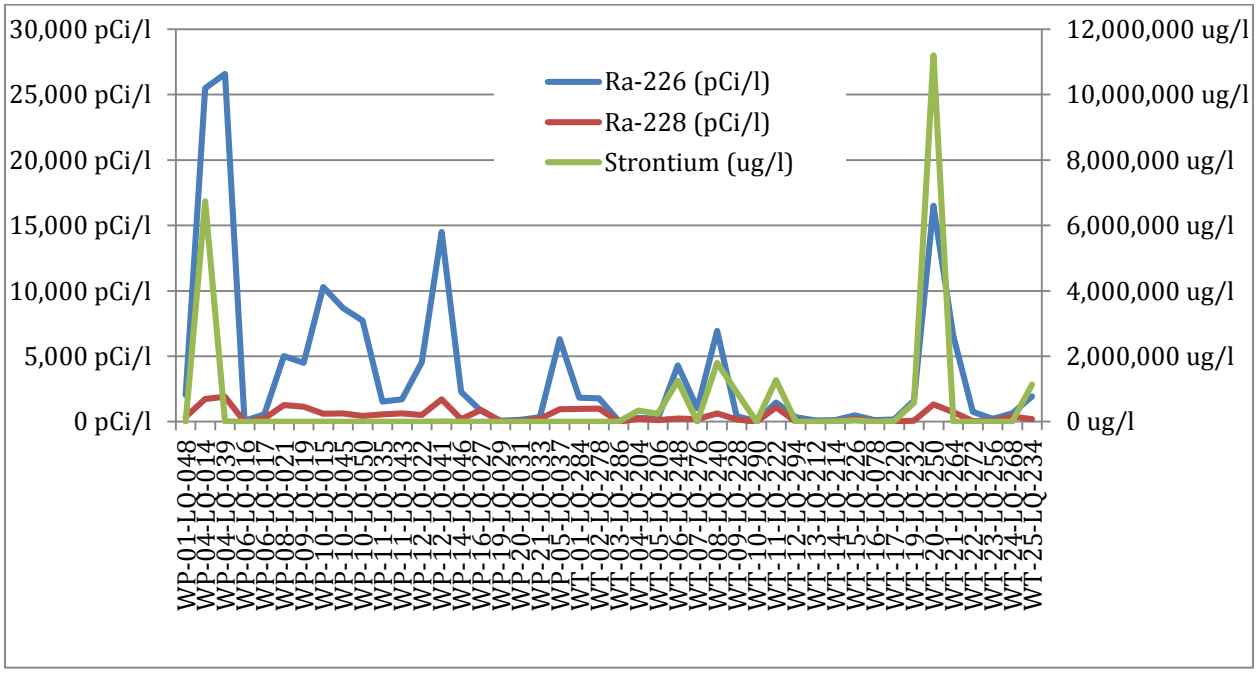


Strontium

Strontium is an alkaline earth metal with chemical properties similar to calcium and barium. It occurs naturally in the minerals celestine, putnisite, and strontianite. Strontium commonly occurs in nature, the 15th most abundant element on Earth, estimated to average approximately 360 ppm in the Earth's crust.

The Pearson correlation was calculated for the total data set (44 data points) and for each of the data subsets (see **Table M-15**). For most of the data subsets, there was a significant correlation between strontium and radium values. The data sets for production fluid, flowback fluid, hydraulic fracturing fluid, and influent display strong to very strong correlations between the strontium and radium values; however, these results are based on very small data sets and could be anomalies. When the entire data set is evaluated, there is (at best) only a very weak correlation. The effluent data has, essentially, no correlation between strontium and radium values. **Figure M-14** provides a graphic depiction of the relationship between radium and strontium.

Figure M-14. Radium Concentration Verse Strontium



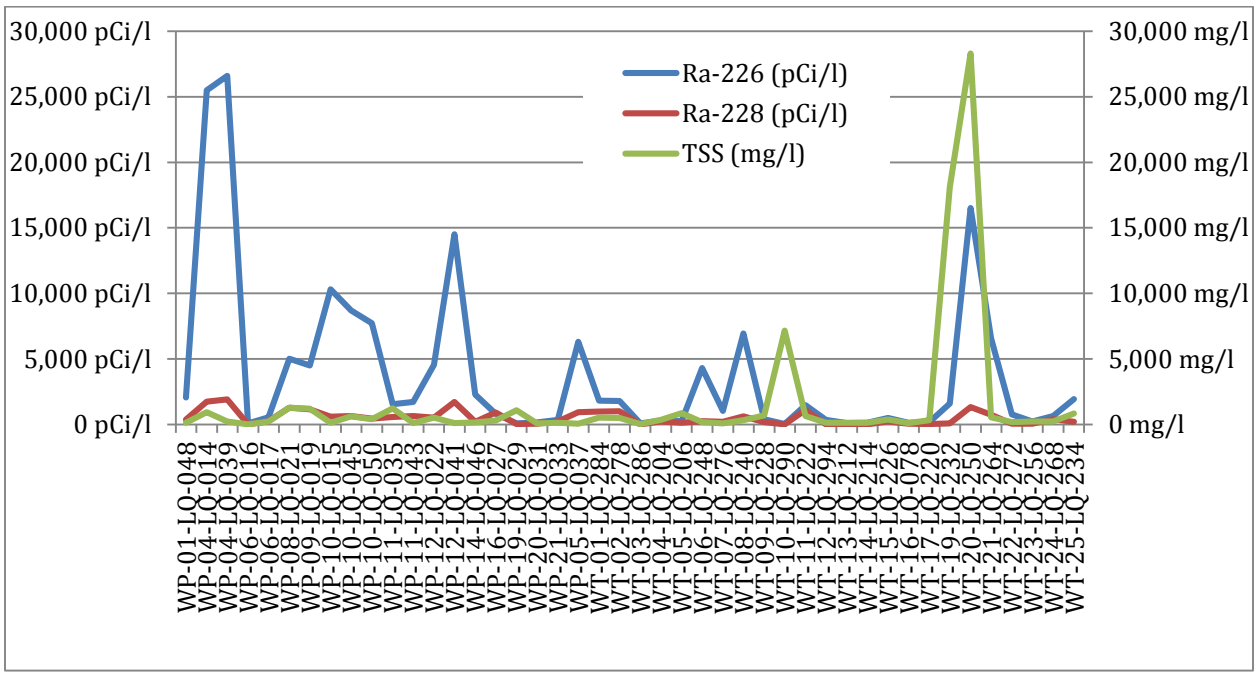
Other Water Quality (TSS and Chloride)

Total Suspended Solids

The term "total solids" refers to matter suspended or dissolved in water and is related to both specific conductance and turbidity. Total suspended solids (TSS) is the portion of total solids retained by a filter and TDS is the portion that passes through a filter.

The Pearson correlation was calculated for the total data set (44 data points) and for each of the data subsets (see **Table M-16**). For most of the data, there was no significant correlation between TSS and radium values. Flowback water displayed a strong correlation between TSS and Ra-226; however, there was not a good correlation between TSS and the chemically identical Ra-228 which would tend to support the conjecture that the observed correlation was likely an anomaly caused by the small data set. **Figure M-15** provides a graphic depiction of the relationship between radium and TSS.

Figure M-15. Radium Concentration Verse Total Suspended Solids

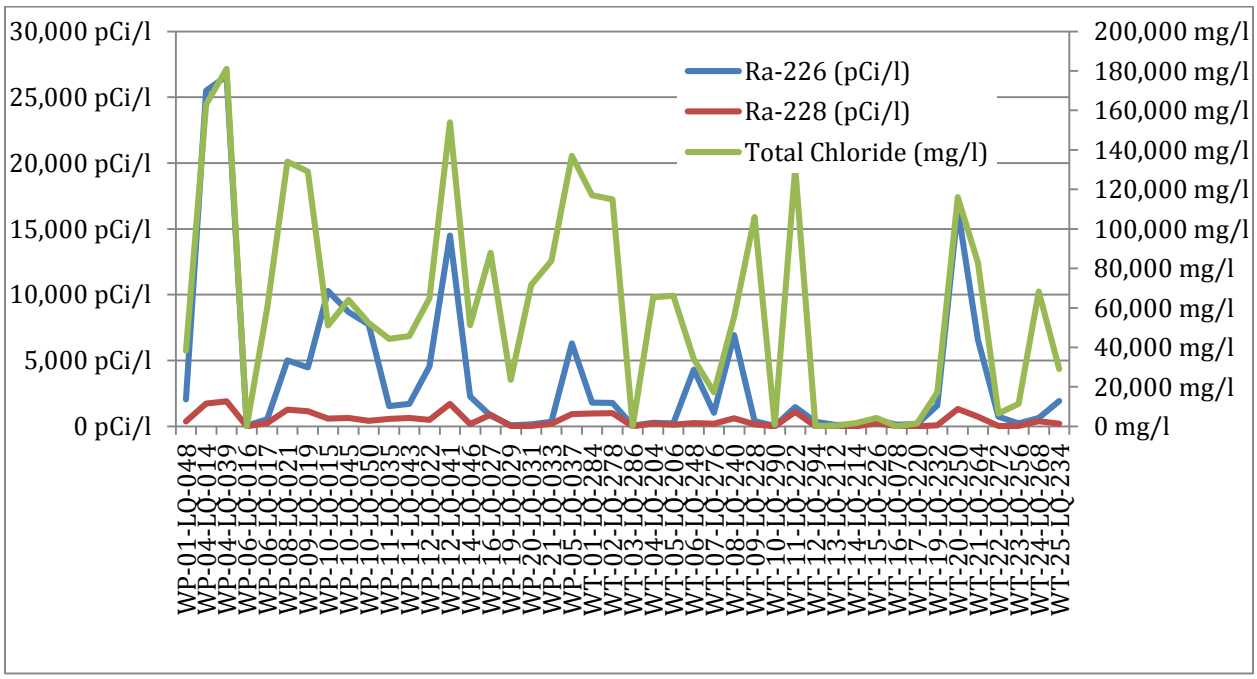


Total Chloride

The chloride ion is the anion (negatively charged ion) Cl^-. It is formed when the element chlorine (a halogen) gains an electron (becomes ionized) or when a compound such as hydrogen chloride is dissolved in water.

The Pearson correlation was calculated for the total data set (44 data points) and for each of the data subsets (see **Table M-17**). Most of the data seemed to show a strong correlation between total chloride concentration and radium concentration with hydraulic fracturing fluid displaying a perfect positive correlation and flowback water having a very strong correlation. While these results are interesting, they are generated from a very small data set and, therefore, should be treated as suspect until confirmed by additional data. Additionally, when the entire data set was evaluated, the correlation was not strong and varied between the chemically identical Ra-226 and Ra-228. **Figure M-16** provides a graphic depiction of the relationship between radium and chloride.

Figure M-16. Radium Concentration Verse Total Chloride



Radiological Parameters

The radiological parameters evaluated in this study are gross alpha and gross beta.

Gross Alpha and Gross Beta

Gross Alpha

Gross alpha is the total radioactivity due to alpha particle activity. The alpha particle is composed of two protons and two neutrons bound together in a particle identical to a helium nucleus.

The Pearson correlation was calculated for the total data set (44 data points) and for each of the data subsets (see **Table M-18**). Most of the data displayed a strong correlation between total alpha emission and radium concentration. This is not surprising as Ra-226 emits alpha, beta, and gamma as it decays. Ra-228 is a beta emitter; however, its short-lived daughter products emit alpha, beta, and gamma as they decay. The correlation between total alpha and radium concentration for the total data set was not as strong. **Figure M-17** provides a graphic depiction of the relationship between radium and gross alpha. When the data was scatter plotted, a gross alpha/Ra-226 outlier was noticed. With the outlier included, the R^2 value was 0.682; however, with the outlier removed, the R^2 value was 0.803. **Figure M-18** provides a graphic depiction of the X-Y scatter plot of the Ra-226 versus gross alpha with the outlier present. **Figure M-19** provides a graphic depiction of the X-Y scatter plot of the Ra-226 versus gross alpha with the outlier removed.

Figure M-17. Radium Concentration Verse Gross Alpha

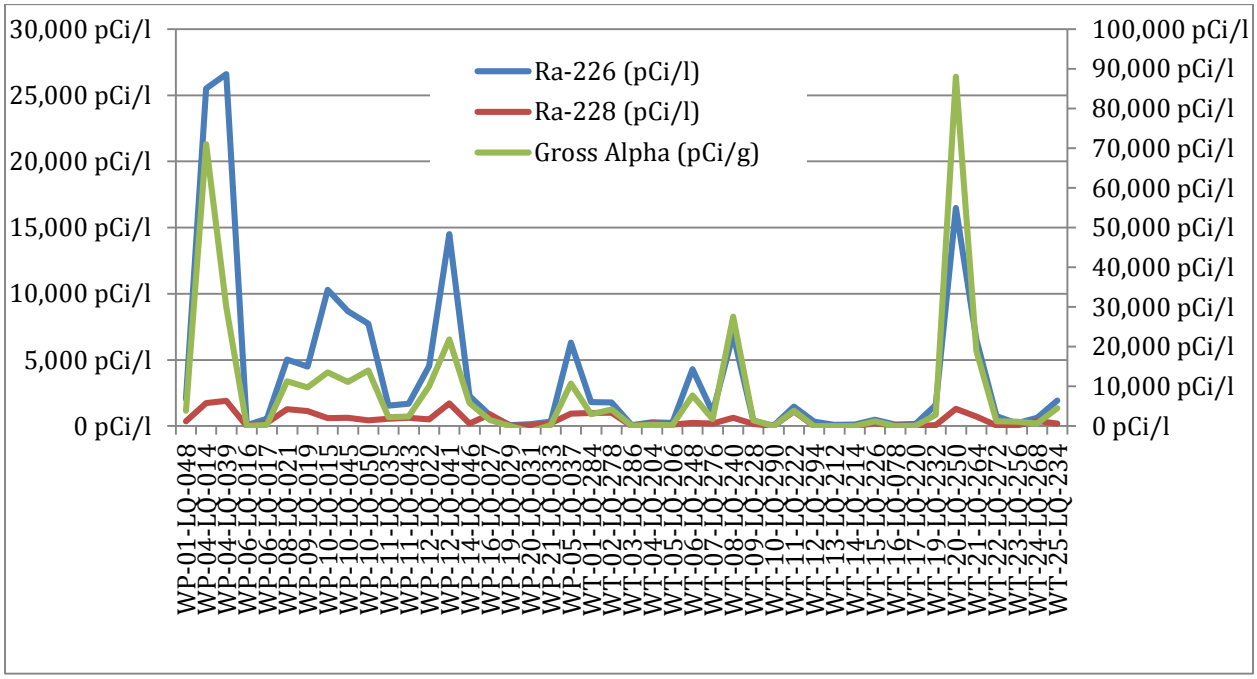


Figure M-18. Ra-226 X-Y Scatter Plot Radium versus Gross Alpha – Outlier Present

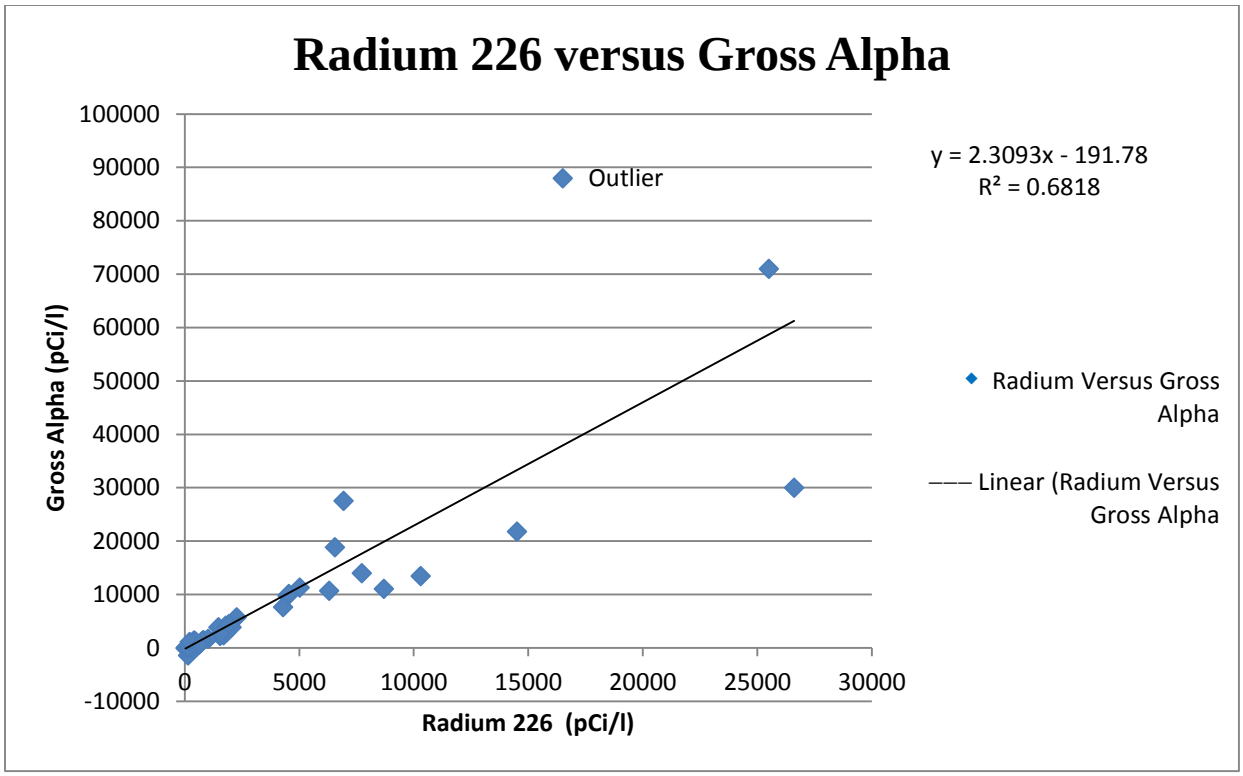
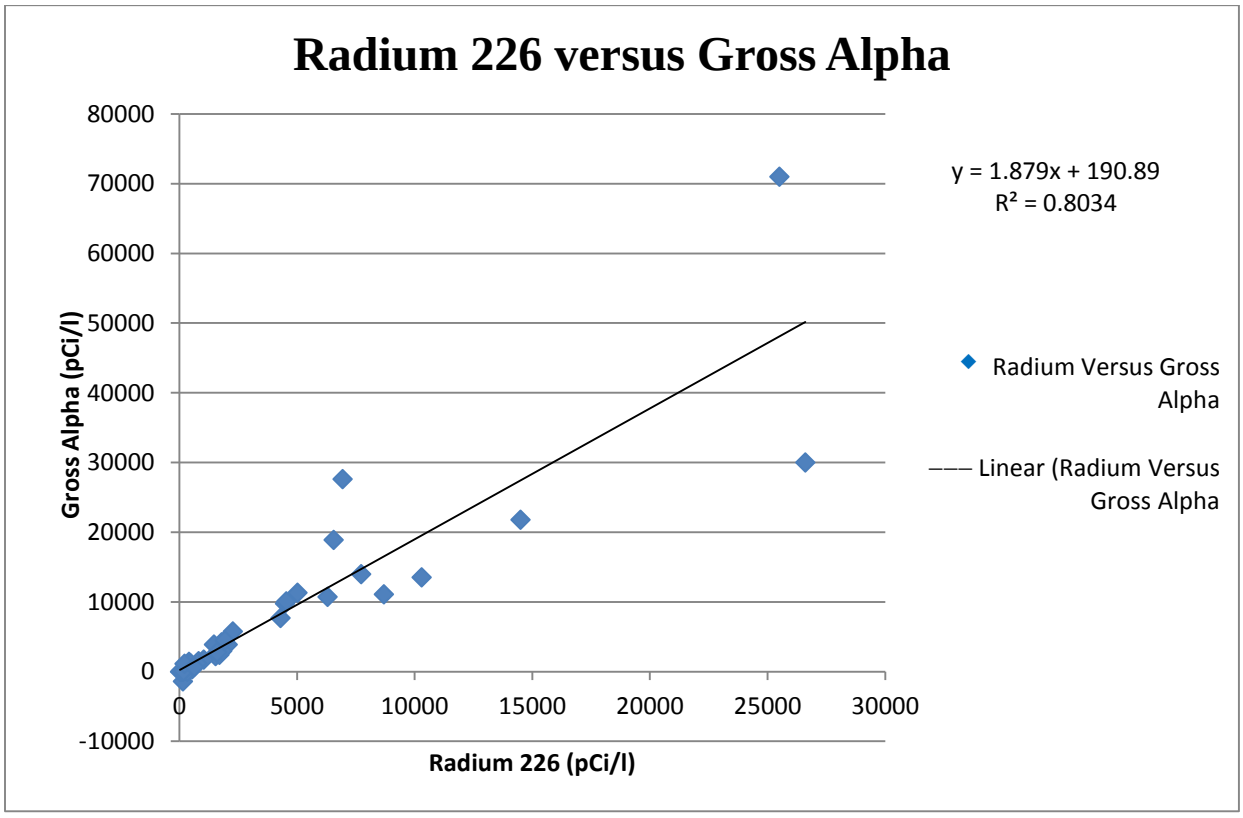


Figure M-19. Ra-226 X-Y Scatter Plot versus Gross Alpha – Outlier Removed

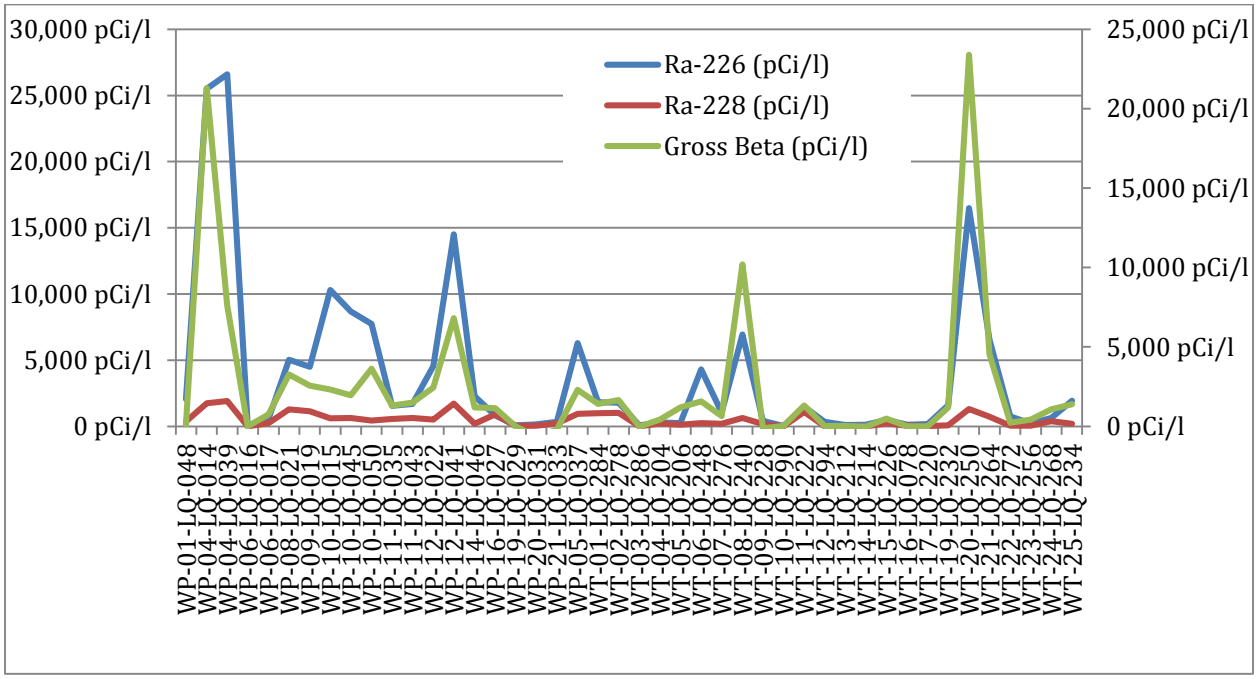


Gross Beta

Gross beta is the total radioactivity due to beta particle activity. A beta particle is a high-energy, high-speed electron or positron emitted by certain types of radioactive nuclei.

The Pearson correlation was calculated for the total data set (44 data points) and for each of the data subsets (see **Table M-19**). The data displayed a strong correlation between total beta emission and radium concentration. This is not surprising as Ra-226 emits alpha, beta, and gamma as it decays. Ra-228 is a beta emitter; however, its short-lived daughter products emit alpha, beta, and gamma as they decay. **Figure M-20** provides a graphic depiction of the relationship between radium and gross beta.

Figure M-20. Radium Concentration Verse Gross Beta



Summary

Radium values were compared to values for various non-radiological water quality parameters (hardness, pH, specific conductance , TDS, TSS, total chloride, Ba, Ca, Fe, K, Mg, Mn, Na, and Sr), as well as gross alpha and gross beta values to determine if statistically significant correlations existed. The results for the entire data set (44 samples) are shown in **Table M-20**.

The limited sample quantity, 44 samples, reduces the reliability of the correlations discussed above. However, the correlation of radium concentration with barium concentration as well as total chloride (by colorimetric method) could be considered for additional future evaluation.

Table M-1. Non-Radiological Parameter Analytical Results – Metals

Study ID	XRF for Ca, Mg, NA, K, Ba, Fe, Mn, Sr [a]	Calcium Total (mg/l)	Magnesium Total (mg/l)	Sodium Total (mg/l)	Potassium Total (mg/l)	Barium Total (mg/l)	Iron Total (mg/l)	Manganese Total (mg/l)	Strontium (µg/l)
WP-01-LQ-048	X	1,480	2,650	4,570	43.7	5,230	144	15.1	1,240
WP-04-LQ-014		24,200	1,830	55,000	199	14,500	119	6.17	6,740,000
WP-04-LQ-039	X	20,500	10,600	15,700	202	12,700	525	18.7	6,030
WP-05-LQ-037	X	21,400	10,400	23,800	382	2.00	437	26.4	2,570
WP-06-LQ-016	X	33.9	184	1,010	29.4	2.00	39.3	7.40	0.500
WP-06-LQ-017	X	10,300	5,570	18,400	294	2.00	129	35.2	1,090
WP-08-LQ-021	X	21,900	14,100	7,970	296	152	252	46.4	3,380
WP-09-LQ-019	X	18,800	9,020	21,600	314	133	238	40.6	3,350
WP-10-LQ-015	X	4,460	4,150	14,600	161	5,040	880	18.7	1,800
WP-10-LQ-045	X	4,420	3,880	8,980	106	10,400	95.5	13.2	1,900
WP-10-LQ-050	X	1,770	2,210	5,520	75.1	11,500	110	2,210	1,450
WP-11-LQ-035	X	2,360	4,950	22,100	389	948	143	12.7	1,980
WP-11-LQ-043	X	2,970	2,980	8,980	484	804	245	12.4	2,190
WP-12-LQ-022	X	4,920	3,500	12,200	88.2	9,120	122	20.4	2,270
WP-12-LQ-041	X	14,800	7,400	7,550	156	15,400	486	19.8	6,180
WP-14-LQ-046	X	4,340	4,220	6,530	219	2.00	42.2	7.80	862
WP-16-LQ-027	X	8,190	7,750	3,360	90.1	2.00	198	21.7	162
WP-19-LQ-029	X	1,710	1,690	9,890	40.7	2.00	116	6.50	31.3
WP-20-LQ-031	X	5,840	4,930	13,900	68.0	2.00	303	14.0	64.3
WP-21-LQ-033	X	8,610	6,320	8,030	70.0	2.00	375	25.3	118
WT-01-LQ-284	X	12,400	9,620	994	328	951	388	48.9	1,160
WT-02-LQ-278	X	11,700	6,600	2,900	298	837	910	79.1	872
WT-03-LQ-286	X	218	426	1,010	19.8	2.00	821	25.1	1.90
WT-04-LQ-204		9,120	1,270	30,400	329	21.1	30.3	8.55	337,000
WT-05-LQ-206		10,900	1,650	27,100	469	14.4	52.9	5.87	240,000
WT-06-LQ-248		34,600	236	14,800	131	2,570	39.5	2.71	1,250,000
WT-07-LQ-276	X	1,570	1,390	15,800	101	573	36.9	7.30	848
WT-08-LQ-240		6,000	440	27,100	118	2,190	79.0	4.69	1,800,000
WT-09-LQ-228		16,100	1,430	48,000	128	142	6.71	1.05	897,000
WT-10-LQ-290	X	212	99.2	1,140	27.0	2.00	128	3.50	0.800
WT-11-LQ-222		17,100	2,050	52,000	145	632	52.7	14.0	1,270,000

Table M-1. Non-Radiological Parameter Analytical Results – Metals

Study ID	XRF for Ca, Mg, NA, K, Ba, Fe, Mn, Sr [a]	Calcium Total (mg/l)	Magnesium Total (mg/l)	Sodium Total (mg/l)	Potassium Total (mg/l)	Barium Total (mg/l)	Iron Total (mg/l)	Manganese Total (mg/l)	Strontium (µg/l)
WT-12-LQ-294	X	266	176	12,800	54.1	2.00	48.5	9.40	1.10
WT-13-LQ-212		31.1	5.57	272	18.5	0.250	2.82	0.490	320
WT-14-LQ-214		214	29.4	627	23.2	3.39	3.60	0.230	10,700
WT-15-LQ-226		567	69.6	2,060	12.3	21.0	19.8	5.71	39,400
WT-16-LQ-078		36.6	7.20	77.3	11.7	0.200	0.750	0.120	250
WT-17-LQ-220		238	28.6	724	13.3	7.68	4.00	0.390	15,400
WT-19-LQ-232		3,810	505	8,440	684	1,200	1,000	14.9	579,000
WT-20-LQ-250		41,500	1,800	99,500	267	24,600	1,610	27.5	11,200,000
WT-21-LQ-264	X	7,430	5,190	9,450	407	3,620	988	21.8	2,500
WT-22-LQ-272	X	378	497	8,780	45.8	225	1,460	6.30	223
WT-23-LQ-256	X	949	827	10,900	68.8	2.00	35.4	2.50	425
WT-24-LQ-268	X	6,240	4,580	1,410	295	301	2,520	29.0	733
WT-25-LQ-234		3,080	223	14,400	129	2,540	15.7	1.83	1,130,000

[a] An "X" signifies that the analysis was performed by XRF. All other analyses were performed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

Table M-2. Non-Radiological Parameters – Water Quality

Study ID	Hardness Total (mg/l)	pH (Electro -metric)	Specific Conductivity @ 25.0 C (umhos/cm)	Total Suspended Solids (mg/l)	Total Dissolved Solids @ 180C BY USGS-I-1750 (mg/l)	Total Chloride-Colorimetric (mg/l)[a]
WP-01-LQ-048	14,600	6.50	72,400	126	72,400	38,400
WP-04-LQ-014	68,100	5.10	112,000	936	313,000	163,000
WP-04-LQ-039	95,000	5.80	1.00	228	317,000	181,000
WP-05-LQ-037	96,400	6.10	1.00	56.0	237,000	137,000
WP-06-LQ-016	841	7.60	308	5.00	186	20.1
WP-06-LQ-017	48,500	6.70	125,000	212	111,000	60,000
WP-08-LQ-021	113,000	6.00	1.00	1,260	255,000	134,000
WP-09-LQ-019	84,100	5.90	1.00	1,200	242,000	129,000
WP-10-LQ-015	28,200	6.40	110,000	120	90,100	51,100
WP-10-LQ-045	27,000	6.40	120,000	602	121,000	64,000
WP-10-LQ-050	13,500	6.30	100,000	388	101,000	52,400
WP-11-LQ-035	26,300	6.60	97,300	1,230	76,700	44,300
WP-11-LQ-043	19,700	6.50	91,700	100	75,100	45,800
WP-12-LQ-022	26,700	6.20	136,000	508	123,000	64,900
WP-12-LQ-041	67,400	6.00	1.00	104	280,000	154,000
WP-14-LQ-046	28,200	6.20	97,800	148	93,800	51,200
WP-16-LQ-027	52,300	6.30	163,000	304	155,000	87,900
WP-19-LQ-029	11,200	6.80	57,000	1,070	43,100	23,600
WP-20-LQ-031	34,900	5.60	135,000	82.0	122,000	71,700
WP-21-LQ-033	47,500	5.20	155,000	136	136,000	83,900
WT-01-LQ-284	70,400	5.20	112,000	512	202,000	117,000
WT-02-LQ-278	56,400	4.90	112,000	494	190,000	115,000
WT-03-LQ-286	2,300	2.80	7,180	16.0	9,330	77.7
WT-04-LQ-204	28,000	6.20	112,000	334	111,000	65,300
WT-05-LQ-206	34,000	6.90	112,000	868	112,000	66,100
WT-06-LQ-248	87,400	6.80	78,700	184	70,200	34,100
WT-07-LQ-276	9,650	7.40	41,800	72.0	31,600	17,300
WT-08-LQ-240	16,800	6.70	112,000	308	111,000	55,500
WT-09-LQ-228	46,100	7.60	112,000	686	194,000	106,000
WT-10-LQ-290	937	6.70	4,570	7,150	4,160	924
WT-11-LQ-222	51,200	5.80	112,000	628	218,000	131,000
WT-12-LQ-294	1,390	7.50	1,400	114	758	275
WT-13-LQ-212	101	8.80	1,350	136	838	329
WT-14-LQ-214	656	7.80	4,280	120	2,860	1,610
WT-15-LQ-226	1,700	7.60	12,000	376	7,810	4,200
WT-16-LQ-078	121	7.20	775	90.0	468	93.8
WT-17-LQ-220	713	7.70	5,100	316	3,220	1,590
WT-19-LQ-232	11,600	9.00	39,900	18,100	21,200	17,300
WT-20-LQ-250	111,000	6.70	112,000	28,300	239,000	116,000
WT-21-LQ-264	39,900	6.20	112,000	530	148,000	82,900
WT-22-LQ-272	2,990	5.40	18,100	168	15,500	6,600
WT-23-LQ-256	5,770	8.20	29,500	216	24,400	11,400
WT-24-LQ-268	34,400	5.70	112,000	230	130,000	68,200
WT-25-LQ-234	8,630	7.00	69,600	830	50,200	29,000

Table M-3. Radium Data

Study ID	Ra-226 (pCi/l)	Ra-228 (pCi/l)	Gross α (pCi/l)	Gross β (pCi/l)
WP-01-LQ-048	2,050	366	3,890	115
WP-04-LQ-014	25,500	1,740	71,000	21,300
WP-04-LQ-039	26,600	1,900	30,000	7,600
WP-05-LQ-037	64.0	1.00	10,700	2,300
WP-06-LQ-016	551	248	-1.49	4.41
WP-06-LQ-017	5,020	1,280	338	732
WP-08-LQ-021	4,490	1,140	11,300	3,270
WP-09-LQ-019	10,300	600	9,760	2,570
WP-10-LQ-015	8,690	633	13,500	2,310
WP-10-LQ-045	7,730	434	11,100	1,960
WP-10-LQ-050	1,540	564	14,000	3,620
WP-11-LQ-035	1,700	636	2,250	1,320
WP-11-LQ-043	4,550	507	2,420	1,500
WP-12-LQ-022	14,500	1,710	10,100	2,440
WP-12-LQ-041	2,270	189	21,800	6,810
WP-14-LQ-046	819	896	5,760	1,200
WP-16-LQ-027	76.0	26.0	1,510	1,140
WP-19-LQ-029	145	42.0	-33.7	-8.86
WP-20-LQ-031	340	214	-1,390	-659
WP-21-LQ-033	6,300	941	257	-192
WT-01-LQ-284	1,820	984	2,940	1,420
WT-02-LQ-278	1,790	1,010	4,220	1,650
WT-03-LQ-286	66.0	6.00	102	-20.6
WT-04-LQ-204	286	228	346	421
WT-05-LQ-206	238	126	252	1,200
WT-06-LQ-248	4,300	250	7,700	1,570
WT-07-LQ-276	1,030	203	1,740	638
WT-08-LQ-240	6,940	623	27,600	10,200
WT-09-LQ-228	404	166	1,410	-123
WT-10-LQ-290	35.0	3.00	-9.62	17.6
WT-11-LQ-222	1,470	1,100	3,880	1,320
WT-12-LQ-294	345	7.00	-30.3	21.9
WT-13-LQ-212	96.0	4.00	4.3	14.5
WT-14-LQ-214	120	9.00	-32.2	-10.9
WT-15-LQ-226	479	227	1,190	493
WT-16-LQ-078	131	41.0	0.556	7.5
WT-17-LQ-220	178	20.0	53.8	-6.61
WT-19-LQ-232	1,600	81.0	2,800	1,180
WT-20-LQ-250	16,500	1,310	88,000	23,400
WT-21-LQ-264	6,560	727	18,900	4,530
WT-22-LQ-272	750	43.0	1,240	231
WT-23-LQ-256	221	41.0	1,120	423
WT-24-LQ-268	632	388	654	1,060
WT-25-LQ-234	1,930	199	4,470	1,400

Table M-4. Hardness

Hardness	All Data (44)	Production Fluid (12)	Flowback Water (5)	Hydraulic Fracturing Fluid (3)	Influent (19)	Effluent (5)
Minimum (mg/l)	101	11,200	26,300	841	101	2,300
Maximum (mg/l)	113,000	113,000	68,100	28,200	111,000	70,400
Average (mg/l)	34,670	54,100	39,300	19,080	20,800	45,300
Median (mg/l)	27,500	49,900	27,000	28,200	8,630	51,200
Standard Deviation (mg/l)	32,650	36,500	18,700	15,800	30,800	25,700
Ra-226 Correlation	0.557	0.486	0.728	0.667	0.797	0.853
Ra-228 Correlation	0.783	0.762	0.712	0.742	0.772	0.788

Table M-5. Calcium

Calcium (Ca) ICP Method	All Data (44)	Production Fluid (12)	Flowback Water (5)	Hydraulic Fracturing Fluid (3)	Influent (19)	Effluent (5)
Minimum (mg/l)	31.1	1,480	2,360	33.9	31.1	218
Maximum (mg/l)	41,500	21,900	24,200	4,460	41,500	17,100
Average (mg/l)	8,360	10,700	9,240	2,940	6,690	11,500
Median (mg/l)	4,690	8,400	4,920	4,340	1,570	12,400
Standard Deviation (mg/l)	9,590	8,301	8,860	2,520	11,600	6,720
Ra-226 Correlation	0.568	0.532	0.857	0.684	0.782	0.514
Ra-228 Correlation	0.664	0.778	0.837	0.757	0.709	0.565

Table M-6. Magnesium

Magnesium (Mg) ICP Method	All Data (44)	Production Fluid (12)	Flowback Water (5)	Hydraulic Fracturing Fluid (3)	Influent (19)	Effluent (5)
Minimum (mg/l)	5.57	1,690	1,830	184	5.57	426
Maximum (mg/l)	14,100	14,100	5,570	4,220	5,190	9,620
Average (mg/l)	3,350	6,670	3,950	2,850	1,001	4,025
Median (mg/l)	1,940	6,860	3,880	4,150	440	2,050
Standard Deviation (mg/l)	3,520	3,920	1,440	2,310	1,490	3,920
Ra-226 Correlation	0.100	0.079	-0.690	0.985	0.565	0.658
Ra-228 Correlation	0.004	-0.176	-0.757	0.961	0.708	0.525

Table M-7. pH

pH	All Data (44)	Production Fluid (12)	Flowback Water (5)	Hydraulic Fracturing Fluid (3)	Influent (19)	Effluent (5)
Minimum	2.80	5.20	5.10	6.20	5.40	2.80
Maximum	9.00	6.80	6.70	7.60	9.00	7.60
Average	6.50	6.08	6.20	6.73	7.13	5.26
Median	6.45	6.05	6.40	6.40	7.00	5.20
Standard Deviation	1.09	0.437	0.644	0.757	0.947	1.73
Ra-226 Correlation	-0.243	-0.182	-0.968	-0.562	-0.235	0.145
Ra-228 Correlation	-0.402	-0.156	-0.964	-0.646	-0.373	0.151

Table M-8. Specific Conductance

Specific Conductance	All Data (44)	Production Fluid (12)	Flowback Water (5)	Hydraulic Fracturing Fluid (3)	Influent (19)	Effluent (5)
Minimum (µmhos/cm)	1.00	1.00	97,300	308	775	7,180
Maximum (µmhos/cm)	163,000	163,000	136,000	110,200	112,000	112,000
Average (µmhos/cm)	68,300	64,500	118,000	69,400	51,500	90,960
Median (µmhos/cm)	85,200	64,700	120,200	97,800	39,900	112,000
Standard Deviation (µmhos/cm)	53,600	64,500	14,500	60,200	47,500	46,800
Ra-226 Correlation	0.028	-0.582	-0.149	0.740	0.552	0.712
Ra-228 Correlation	0.105	-0.686	-0.312	0.807	0.698	0.692

Table M-9. Total Dissolved Solids (TDS)

Total Dissolved Solids (TDS)	All Data (44)	Production Fluid (12)	Flowback Water (5)	Hydraulic Fracturing Fluid (3)	Influent (19)	Effluent (5)
Minimum (mg/l)	186	43,100	76,700	186	468	9,330
Maximum (mg/l)	316,000	317,000	313,000	93,800	23,900	218,00
Average (mg/l)	110,400	170,000	149,000	61,400	57,000	163,000
Median (mg/l)	106,000	146,000	121,000	90,100	24,400	194,000
Standard Deviation (mg/l)	92,700	92,100	93,800	53,000	67,100	86,400
Ra-226 Correlation	0.220	0.730	0.307	0.518	0.687	0.490
Ra-228 Correlation	0.127	0.068	0.480	0.605	0.579	0.509

Table M-10. Sodium (Na)

Sodium (Na) ICP Method	All Data (44)	Production Fluid (12)	Flowback Water (5)	Hydraulic Fracturing Fluid (3)	Influent (19)	Effluent (5)
Minimum (mg/l)	77.3	3,360	8,980	1,010	77.3	994
Maximum (mg/l)	99,500	23,800	55,000	14,600	99,500	52,000
Average (mg/l)	15,000	10,900	23,300	7,380	15,040	21,000
Median (mg/l)	9,220	8,510	18,400	6,530	9,450	2,900
Standard Deviation (mg/l)	18,600	6,550	18,400	6,830	22,600	26,500
Ra-226 Correlation	0.445	0.230	0.835	0.978	0.852	-0.156
Ra-228 Correlation	0.400	0.240	0.901	0.995	0.806	0.010

Table M-11. Potassium (K)

Potassium (K) ICP Method	All Data (44)	Production Fluid (12)	Flowback Water (5)	Hydraulic Fracturing Fluid (3)	Influent (19)	Effluent (5)
Minimum (mg/l)	11.7	40.7	88.2	29.4	11.7	19.8
Maximum (mg/l)	684	484	389	219	684	328
Average (mg/l)	178	185	215	136	169	184
Median (mg/l)	129	123	199	161	101	145
Standard Deviation (mg/l)	157	150	127	97.1	190	128
Ra-226 Correlation	0.123	0.127	-0.314	0.414	0.233	0.899
Ra-228 Correlation	0.315	0.417	-0.150	0.508	0.306	0.765

Table M-12. Barium (Ba)

Barium (Ba) ICP Method	All Data (44)	Production Fluid (12)	Flowback Water (5)	Hydraulic Fracturing Fluid (3)	Influent (19)	Effluent (5)
Minimum (mg/l)	0.200	2.00	2.00	2.00	0.200	2.00
Maximum (mg/l)	24,600	15,400	14,500	5,040	24,600	951
Average (mg/l)	2,870	3,830	6,990	1,680	1,994	513
Median (mg/l)	189	143	9,120	2.00	21.1	632
Standard Deviation (mg/l)	5,420	5,900	6,280	2,909	5,590	421
Ra-226 Correlation	0.824	0.786	0.849	0.979	0.929	0.992
Ra-228 Correlation	0.619	0.532	0.767	0.952	0.860	0.937

Table M-13. Iron (Fe)

Iron (Fe) ICP Method	All Data (44)	Production Fluid (12)	Flowback Water (5)	Hydraulic Fracturing Fluid (3)	Influent (19)	Effluent (5)
Minimum (mg/l)	0.750	110	95.5	39.3	0.750	6.71
Maximum (mg/l)	2,520	525	143	880	2,520	910
Average (mg/l)	347	285	122	320	425	436
Median (mg/l)	125	248	122	42.2	39.5	388
Standard Deviation (mg/l)	517	142	17.3	485	732	420
Ra-226 Correlation	0.168	0.665	-0.366	0.979	0.377	0.037
Ra-228 Correlation	0.186	0.642	-0.182	0.952	0.484	-0.066

Table M-14. Manganese (Mn)

Manganese (Mn) ICP Method	All Data (44)	Production Fluid (12)	Flowback Water (5)	Hydraulic Fracturing Fluid (3)	Influent (19)	Effluent (5)
Minimum (mg/l)	0.120	6.50	6.17	7.40	0.120	1.05
Maximum (mg/l)	2,210	2,210	35.2	18.7	29.0	79.1
Average (mg/l)	66.0	205	17.5	11.3	8.042	33.6
Median (mg/l)	13.0	20.8	13.2	7.80	5.71	25.1
Standard Deviation (mg/l)	331	632	11.1	6.41	8.94	30.9
Ra-226 Correlation	0.100	0.079	-0.690	0.985	0.565	0.658
Ra-228 Correlation	0.004	-0.176	-0.757	0.961	0.708	0.525

Table M-15. Strontium (Sr)

Strontium (Sr) ICP Method	All Data (44)	Production Fluid (12)	Flowback Water (5)	Hydraulic Fracturing Fluid (3)	Influent (19)	Effluent (5)
Minimum (µg/l)	0.500	31.3	1,090	0.500	0.800	1.90
Maximum (µg/l)	11,200,000	6,180	6,740,000	1,800	11,200,000	1,270,000
Average (µg/l)	581,000	2,230	1,350,000	888	874,000	434,000
Median (µg/l)	1,940	1,820	1,980	862	10,700	1,160
Standard Deviation (µg/l)	1,960,000	2,190	3,010,000	900	2,560,000	608,000
Ra-226 Correlation	0.536	0.857	0.951	0.957	0.905	-0.088
Ra-228 Correlation	0.388	0.924	0.968	0.983	0.822	0.103

Table M-16. Total Suspended Solids (TSS)

Total Suspended Solids (TSS)	All Data (44)	Production Fluid (12)	Flowback Water (5)	Hydraulic Fracturing Fluid (3)	Influent (19)	Effluent (5)
Minimum (mg/l)	5.00	56.0	212	5.00	72.0	16.0
Maximum (mg/l)	28,300	1,260	1,230	148	28,300	686
Average (mg/l)	1,580	421	698	91.0	3,070	467
Median (mg/l)	306	182	602	120	308	512
Standard Deviation (mg/l)	5,010	468	394	75.8	7,460	265
Ra-226 Correlation	0.686	0.730	0.967	0.641	0.796	0.721
Ra-228 Correlation	0.127	0.068	0.480	0.605	0.579	0.509

Table M-17. Total Chloride Colorimetric Method

Total Chloride Colorimetric Method	All Data (44)	Production Fluid (12)	Flowback Water (5)	Hydraulic Fracturing Fluid (3)	Influent (19)	Effluent (5)
Minimum (mg/l)	20.1	23,600	44,300	20.1	93.8	77.7
Maximum (mg/l)	181,000	181,000	163,000	51,200	116,000	131,000
Average (mg/l)	61,050	95,000	79,300	34,100	30,500	93,900
Median (mg/l)	54,000	86,000	64,000	51,100	17,300	115,000
Standard Deviation (mg/l)	51,400	5,009	47,700	29,500	34,800	53,200
Ra-226 Correlation	0.653	0.802	0.966	1.00	0.742	0.766
Ra-228 Correlation	0.894	0.889	0.948	1.00	0.863	0.779

Table M-18. Gross Alpha

Gross Alpha	All Data (44)	Production Fluid (12)	Flowback Water (5)	Hydraulic Fracturing Fluid (3)	Influent (19)	Effluent (5)
Minimum (pCi/l)	-1,390	-1,390	338	0.645	-32.2	102
Maximum (pCi/l)	88,000	30,000	71,000	1,510	88,000	4,220
Average (pCi/l)	8,790	8,680	19,000	766	8,210	2,510
Median (pCi/l)	2,340	6,830	10,100	788	1,120	2,940
Standard Deviation (pCi/l)	17,400	9,670	29,500	755	207	1,730
Ra-226 Correlation	0.826	0.964	0.984	0.973	0.975	0.926
Ra-228 Correlation	0.654	0.860	0.983	0.992	0.918	0.955

Table M-19. Gross Beta

Gross Beta	All Data (44)	Production Fluid (12)	Flowback Water (5)	Hydraulic Fracturing Fluid (3)	Influent (19)	Effluent (5)
Minimum (pCi/l)	-659	-659	742	4.41	-10.9	-123
Maximum (pCi/l)	23,400	7,600	21,300	2,310	23,400	1,650
Average (pCi/l)	2,510	2,340	5,550	1,171	2,460	849
Median (pCi/l)	1,190	1,900	1,960	1,200	493	1,320
Standard Deviation (pCi/l)	4,890	2,670	8,827	1,153	5,610	850
Ra-226 Correlation	0.805	0.928	0.964	0.943	0.966	0.974
Ra-228 Correlation	0.659	0.900	0.978	0.973	0.921	0.969

Table M-20. Summary of Data Set

Analyte/Parameter (all data)	Correlation with Ra-226	Correlation with Ra-228	Correlation Potential
Hardness	0.557	0.783	Modest
Calcium	0.568	0.664	Modest
Magnesium	0.100	0.004	No Correlation
pH	-0.243	-0.402	Weak
Specific Conductance	0.028	0.105	No Correlation
TDS	0.220	0.127	No Correlation
Sodium	0.445	0.400	Weak
Potassium	0.123	0.315	No Correlation
Barium	0.824	0.619	Modest to Strong
Iron	0.168	0.186	No Correlation
Manganese	0.100	0.004	No Correlation
Strontium	0.536	0.388	Weak to Modest
TSS	0.686	0.127	Weak to Modest
Total Chloride	0.653	0.894	Modest to Strong
Gross Alpha	0.826	0.654	Modest to Strong
Gross Beta	0.805	0.659	Modest to Strong