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Water Quality of Wells Near a Coal Ash Impoundment in Juliette, GA

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An abstract of
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Abstract

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Many rural communities rely on dug wells as a primary source of drinking water. This well water is usually untreated, susceptible to natural and anthropogenic contamination, and rarely tested. Well networks near industrial waste sites like coal ash impoundments of coal-fired power plants, may be at higher risk of contamination from waste sites. Coal ash constituents, including trace metals and metalloids, are able to deposit and move through the environment. Using data provided by the Altamaha Riverkeepers (ARK) for 64 wells in Juliette, GA, we sought first, to characterize well contamination from toxic metals, including hexavalent chromium, arsenic, and lead, and second, to investigate contaminant associations with spatial factors including distance and elevation. We found that distance and elevation exhibited negative correlations with a majority of contaminants, including boron, cobalt, and strontium (<-0.20). Results did not exhibit positive correlations above 0.20. Linear regression models found significant negative associations between distance and well depth with boron, cobalt, and strontium. Spatial mapping of hexavalent chromium, barium, and strontium found that the majority of wells in the upper threshold for each contaminant were located between 2-4 miles northeast of the center of the coal ash impoundment. This study suggests that elevation and distance from a coal ash impoundment are significantly associated with specific decreased metal contaminant levels in wells in Juliette, GA. Understanding the nature and extent of metal contamination in drinking water sources is critical to safeguarding public health and the well-being of communities.

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1 Introduction

Coal provides approximately 23% of the electricity in the United States [1]. This sedimentary rock is comprised predominantly of carbon, but also contains hydrogen, oxygen, nitrogen, sulfur, and an array of different trace metals and radioactive elemental contaminants, through its formation over thousands of years largely from plant debris [2].

Coal combustion residuals (CCR), commonly referred to as coal ash, are the byproduct of coal combustion at coal-fired power plants. Coal ash is a fine, dust-like material that consists of particulate matter (PM) containing polycyclic aromatic hydrocarbons, radioactive elements, and toxic metals such as lead, mercury, arsenic, cadmium, chromium, and antimony that become concentrated compared to the original coal material through the combustion process [2]. In 2017, the U.S. produced over 111 million tons of coal ash [3].

Coal ash is a comprehensive term for CCRs produced at coal fired power plants such as flue gas desulfurization solids, boiler slag, bottom ash, and fly ash. As coal combustion takes place at a coal-fired power plant, PM ≤10 µm is pushed upwards through plant stacks where it is collected on filters. This PM, collectively referred to as fly ash, makes up approximately 40%-70% of the coal ash product [4]. Approximately 64% of coal ash was repurposed into industrial products like cement in 2017 [3]. Coal ash that is not repurposed is stored in dry landfills and wet ponds where it can become a pollution source depending on the type of containment and waste practices used.

Although studies on the relationship between coal ash and human health are limited, some recent studies and a literature review have shed new light on the risks that coal ash and coal ash impoundments pose for nearby residential communities, and especially children of those communities. In a 2015 community-based study of 4 neighborhoods near a coal ash impoundment, focus groups revealed that the majority of parents (85%) reported that their children were suffering respiratory, emotional, and behavioral disorders [5]. A 2017 study deployed a cross-sectional survey to children in a community adjacent to coal ash storage sites and a community not living near coal ash storage sites. Results found that the prevalence of sleep and health problems including attention-deficit hyperactivity disorder (ADHD), gastrointestinal problems, difficulty falling asleep, frequent night awakenings, teeth grinding, and complaint of leg cramps were higher ($P<.05$) amongst children living near coal ash compared to children not living near coal ash [6].

While there are no studies investigating the direct relationship between coal ash and children's health, there is a growing body of evidence to support the adverse health outcomes associated with exposure to air pollution containing coal combustion products. In a 2019 cross-sectional epidemiological study, the prevalence of respiratory symptoms was assessed amongst adults exposed to coal ash and non-exposed adults. Results found that the odds of respiratory symptoms including shortness of breath, hoarseness, and respiratory infections were higher in the exposed group versus the non-exposed group. Other respiratory health indicators, perception of health and overall respiratory health scores, were more likely to be reported lower in the exposed group versus the non-exposed group [4]. Further evidence for the health impacts of coal-powered electric plants and coal ash impoundments has been summarized in a 2018 literature review of 30 years of peer-reviewed journal entries. Results of this review revealed higher rates of all-cause and premature mortality, increased risk of respiratory disease and lung cancer, cardiovascular disease, poorer child health, and higher infant mortality for people living in close proximity to coal-fired plants or coal ash impoundments [7].

1.1 Metals and Human Health

Coal-fired power plants can impact human health directly through immediate exposure to polluted air and water and indirectly through exposure to coal and its by-products in the food chain. Emissions from coal-fired power plants known to be associated with adverse health effects include nitrogen oxide (NOx), sulfur dioxide (SO2), particulate matter (PM), toxic metals and radioactive isotopes. Coal ash, a by-product of the coal combustion process, can contain concentrations of metals higher than that of coal itself [8].

Although air pollution from coal-fired power plants remains a pressing concern for environmental health, water and soil contamination are also of great concern. Coal ash contamination of water and soil can come from its deposition into landfills or coal ash ponds and subsequent leaching of pollutants into the surrounding environment [9]. Coal ash contaminants harmful to human and wildlife found in soil and water include polycyclic aromatic hydrocarbons (PAHs), and an array of toxic metals including arsenic (As), mercury (Hg), lead (Pb), cadmium (Cd), vanadium (V), chromium (Cr), nickel (Ni), and zinc (Zn) [10]. Exposure to PAHs and these toxic metals are associated with neurotoxic, carcinogenic, teratogenic, and mutagenic effects [7].

There is limited research on the health effects of coal ash exposure on humans, although studies of the impacts of coal ash based on animal models or *in vitro* experiments have been conducted [11]. Occupational health studies have shown that workers at coal-fired power plants are at higher risk of malignancies, cytogenetic damage, and chromosomal aberrations [7]. Environmental health studies of communities in close proximity to coal ash ponds are less common and largely survey based.

1.2 Coal Ash Ponds

Coal ash is often stored in dry landfills or wet coal ash ponds. Coal ash ponds are a simple mixture of coal ash waste and water, designed to limit the formation of dust in the air. The U.S. produces approximately 130 million tons of coal ash each year, a large portion of which makes its way to the estimated 735 active coal ash ponds across 47 states [12]. Deposition of coal ash in man-made pond impoundments can contaminate surface and groundwater by leaching coal ash pollutants [7]. Some coal ash ponds feature a composite liner set overtop compacted soil that prevents soil and groundwater contamination [6]. More than 95% of coal ash ponds in the US do not have liners and coal ash ponds that do utilize a liner may not have the proper composite liner needed to prevent coal ash leaching [13].

After two coal ash impoundment disasters in Kingston, TN and Eden, NC, spilled over a billion tons of collective coal ash waste into two rivers, the U.S. EPA passed the Disposal of Coal Combustion Residuals from Electric Utilities Final Rule that went into effect in 2016. The final rule established minimum national criteria for coal ash waste storage facilities, including liner requirements for coal ash impoundments, groundwater monitoring around coal ash impoundments, and reporting measures for fugitive coal ash emissions in air, water, and soil [14]. Coal ash is classified as a non-hazardous solid waste under the Resource Conservation and Recovery Act (RCRA) of the EPA [15]. Since coal ash is classified as non-hazardous under the RCRA, it can be stored in open-air impoundments and landfills. Non-hazardous classification also dictates that the federal government does not regulate coal ash, rather each state is responsible for coal ash regulation.

Coal ash impoundments are often located near low income communities [5]. For example, Uniontown, AL has a population of 1,775 (2010 U.S. Census) and is less than four miles away from Arrowhead Landfill where coal ash from the Kingston, TN disaster was sent. Uniontown is approximately 90% African-American with an average median household income 74% lower than the national average.

1.3 Spatial factors of coal ash contamination

Migration of pollutants from waste collection sites to the surrounding environment is a complex process. Research shows that migration of coal ash pollutants from impoundments can be retained by nearby ecosystems [16]. Deposition of coal ash contaminants in soil and sediments can remobilize as environmental changes occur which may prolong or worsen contamination. A study of coal ash effluents including surface water from lakes, rivers, and pore water extracted from lake sediments in North Carolina revealed high levels of coal ash pollutants, some of which were higher than U.S. EPA guidelines for drinking water [17]. Coal ash ponds, especially those that are unlined, can leach pollutants into groundwater systems, threatening aquatic organisms and posing a significant public health threat [9]. The possibility of surface and groundwater contamination by coal ash is a health concern for communities near impoundments, especially rural communities that utilize private water wells as a main drinking water source.

Distance of community water sources from coal ash ponds is a potential spatial factor of contamination. A study of heavy metal contamination in groundwater in India found the attenuation zone, or area where coal ash pond leachate mixes with groundwater, to be 600 – 900m from the pond. This study also revealed that tube well and open well contamination of Mn, Fe, and Pb exceeded USEPA maximum contaminant levels for drinking water [18]. Further research is needed to understand the association between distance from coal ash impoundments and health effects [7].

Access to groundwater from private wells is vital to the health and well-being of rural communities that do not have access to treated municipal or city water systems. However, well water is usually untreated, making it susceptible to environmental contamination [19].

1.4 Study Motivation and Study Area

This study was initiated by the Altamaha Riverkeepers (ARK), a grassroots organization dedicated to protecting, defending, and restoring the Altamaha River in Georgia [20]. The Altamaha River flows eastward towards the Atlantic Ocean from its origin at the confluence of the Oconee River and Ocmulgee River. The community of Juliette, GA and Georgia Power's coal-fired power plant Scherer are located west of the Ocmulgee River.

Juliette, GA is located in Monroe County is approximately 55 miles southeast of Atlanta, GA. The Agency for Toxic Substances and Disease Registry (ATSDR) calculated population information for people living in a 10-mile radius of Juliette, using 2010 US Census data. The population of this region is approximately 12,224, 74% of which is white, non-Hispanic; 25% African American, and <1% are Latino/Hispanic. There are approximately 5,000 housing units and 1,000 children under 6 years of age. The majority or residents (78%) have at least a high school education and have a median yearly income of ~$50,000 [21].

The nearly 75 sq. miles of Juliette, GA has a population of 3,343 with a median age of 50.7 years. The Juliette community is 74.3% white, 21.8% African American, 1.7% Latino/Hispanic, and <1% of all other races. The median household income in Juliette is approximately $60,299 (2010 Census).

Juliette, GA is located two miles from Georgia Power Plant Scherer, the largest coal-fired power plant in the US. Plant Scherer takes up approximately 18.75 sq. miles (12,000 acres) and is surrounded primarily by agricultural and residential land use. This plant is home to three coal ash impoundments, including a 553-acre unlined coal ash pond containing over 15 million tons of coal ash. The coal ash pond, AP-1, opened in 1982 and has since been a cause of concern amongst Juliette residents [22]. Juliette is a rural community and relies on private wells for drinking water and other uses, raising concerns about the potential contamination of drinking water from unlined coal ash disposal impoundments.

1.5 Regional Geology and Hydrogeology

The geology and hydrogeology are important factors for the migration and mobilization of coal ash pollutants in the environment. Juliette, GA and Plant Scherer are located in the Piedmont Physiographic Province (PPP) of Georgia, used to describe the area's land formations, elevation, rocks and minerals, and soil characteristics. The PPP is the second largest province in the state and has the highest population. It lies between the mountains of north Georgia and the Fall Line [23].

Metamorphic and igneous rocks make up the underlying bedrock and weathered layers of the PPP. These rocks have been exposed to physical and chemical weathering, resulting in a landscape marked by creeks and streams that form a dendritic drainage pattern. Bedrock in this region is typically overlain with residual soils and saprolite. The depth of weathering in the PPP is generally 20 – 60 feet, but may extend to depths greater than 100 feet in some areas. The depth of weathering in the PPP can vary significantly due to variations in rock type and structure [22].

Residual soils are formed when rocks weather due to chemicals, water, and other environmental elements and remain in the same location. Residual soils in the PPP largely consist of sandy silt, silty sand, sandy clay, and silty clay, and lie at variable thickness atop the bedrock. Thickness of residual soils in the region determined by boring showed a range of approximately 17 – 168 feet [22].

1.6 Study Objective

A growing body of evidence has highlighted the unique threat that communities adjacent to coal ash impoundments, like Juliette, face. The metal composition of coal ash and its permeability into groundwater is an urgent public health concern, especially for communities that rely on private wells for water. A great deal of research has been done to understand how exposure to metals impacts health and the dangers of emissions from coal-fired power plants. However, few investigations have explored the association between coal ash impoundments and ground water contamination, and even fewer have sought to understand well contamination near coal ash impoundments. This study will first seek to understand the extent to which private wells in Juliette, GA are contaminated with metals. This will be followed by an examination of whether spatial factors, including distance and elevation, are contributing to well contamination.

2. Methods

2.1 Water Sample Collection and Assessment

This study focused on the community of Juliette, GA. Water samples were collected by ARK beginning 13 August 2016 and have continued through 7 February 2020. Samples were collected from household water taps following a standardized protocol and were packaged and transported to PACE Analytical Laboratories in Asheville, NC for analysis. All water samples were taken from households that utilize private water wells as their primary source for water, including drinking water. A total of 64 samples were collected and analyzed in this time period.

Household sampling strategy was based on distance from Plant Scherer AP-1 coal ash pond and agreement from households to test their water. The first six wells tested were all within one mile of the eastern boundary of AP-1. Subsequent water samples were taken from wells progressively further out from AP-1; the furthest being 7.4 miles away. Sampling distribution has generally stayed within a 2-mile radius of AP-1. ARK attributes this strategy to their objective of better understanding the scope of contamination by defining a plume around AP-1 (ARK, 2020).

All samples followed Environmental Protection Agency (EPA) Environmental Sampling and Analytical Methods (ESAM) protocols. Water taps sampled were set for cold output and were free of contaminating devices such as screens, aeration devices, or purification devices. Water was timed to run for a minimum of five minutes before sampling. Plastic bottles were used to collect samples. All samples underwent EPA analytical methods 200.7, 245.1, and 218.7 to determine levels of metals and trace elements, and hexavalent chromium.

2.2 Data Preparation

Well water test data was provided to Emory University by ARK starting in November 2019. The ARK dataset contained censored data consisting of values below their respective limits of detection (LODs) and missing data for variables that were not tested. Censored data consists of unknown values beyond a certain threshold. In this study, censored data refers to data points below the parameter's LOD. These parameters resulted in little variation across observations due to their data points being below the limit of detection (LOD) and/or were not tested for throughout the duration of the sampling time period and therefore were not used in correlation or regression analysis. Censored data points were imputed using their respective LOD divided by the square root of 2, per EPA guidance [24].

2.3 Data Analysis

Well water sample distribution was measured for each variable by visualizing combined histogram, density trace, and boxplot. Summary statistics were calculated that include range, mean, median, standard deviation, kurtosis, skewness, and the coefficient of variation.

In order to examine the linear relationship between spatial and element variables, a Pearson correlation coefficient matrix was produced. A correlation matrix is a useful way to easily visualize and interpret the direction and strength of relationship between two continuous variables [25].

Linear regression analysis was used to model the relationship between spatial independent variables, including distance, elevation, and well depth, and metal contaminant dependent variables.

2.4 Statistics and mapping tools

Spatial distribution patterns of metal contaminants in Juliette, GA wells were mapped to show their respective concentrations using QGIS 3.12 geographic information system software. R Studio was used for data analyses, statistical tests, and plots.

3. Results

3.1 Descriptive well water quality and spatial parameters

The measured element parameters are summarized and compared with respective EPA standards in Table 1. Arsenic, Lead, Beryllium, Cadmium, Molybdenum, Nickel, and Selenium parameters resulted in little variation across observations due to their data points being below the limit of detection (LOD) and/or were not tested for throughout the duration of the sampling time period.

Hexavalent chromium concentrations ranged from 0.00071 – 10.4 ug/L, with a mean value of 1.91 ug/L. There is no national regulation for hexavalent chromium; however, the state of California regulates hexavalent chromium to a maximum contaminant level (MCL) of 50 ug/L. No well water samples detected hexavalent chromium that exceeded the national or California state total chromium MCL.

Aluminum was detected in 7 samples above the detection limit. After imputation of non-detect observations, aluminum ranged from 11 to 230 ug/L, with a mean value of 23.1 ug/L. A total of 4 (6.3%) well-water samples contained aluminum concentrations above 50 ug/L.

Cobalt was detected in 3 samples above the detection limit. After imputation of non-detect observations, cobalt ranged from 1.41 – 10 ug/L, with a mean of 1.74. Cobalt has not been designated an MCL or secondary maximum contaminant level (SMCL) by the EPA. Lead above the EPA MCL of 15 ug/L was detected in one well-water sample. Lead concentrations ranged from 1.8 – 30 ug/L, with a mean of 7.45 ug/L. Manganese was detected in 18 samples, 9 (14%) of which were above the EPA SMCL of 50 ug/L.

Spatial parameters are summarized in Table 2. Elevation is measured in feet above sea level (ASL) from the well sample site calculated using the U.S. Geological Survey (USGS) National Map Elevation tool [26]. Distance is measured in miles from the center of Georgia Power's coal ash pond to each well sample site. Distance was calculated using QGIS (v3.12).

3.2 Correlations between metals detected in wells

Table 3 shows Pearson correlation coefficients for ten element contaminants and two spatial parameters. Hexavalent chromium showed the strongest positive correlation with vanadium (0.65). Strontium showed the strongest negative correlation with elevation (-0.42). Six correlations were ≥0.25 and five correlations were <-0.25. Elevation had a largely negative correlation (80%) with element contaminants. Distance also had a largely negative correlation (70%) with element contaminants.

3.3 Linear regression of metals on the basis of spatial parameters

Table 4 shows linear regression results used to measure the association between spatial predictor variables and metal contaminant outcome variables. Beta coefficients, standard error, and probability values are reported for ten outcome parameters used in the regression analysis. Predictor variables were first regressed individually on metal outcome parameters. Changes in distance are significantly associated with decreases in cobalt per unit change in distance (β = -0.36 ppm/mi, p = 0.007). Changes in distance do not significantly affect other metal outcome parameters in this model at 0.05 significance levels or less. However, hexavalent chromium and aluminum regressed by distance resulted in p-values of 0.08, supporting our a priori hypothesis that distance is associated with metal contamination in wells. Changes in elevation are significantly associated with decreases in hexavalent chromium concentrations (β = -0.01ppm/ft, p = 0.03), decreases in boron (β = -0.10ppm/ft, p = 0.006), and decreases in strontium (β = -0.69ppm/ft, p = 0.0009).

3.4 Spatial distribution of major well water samples

Figures 1-3 show spatial distributions and concentrations of three contaminants detected in well water samples: hexavalent chromium, barium, and strontium. These elements were selected for mapping because they resulted in the least amount of imputed data points below the LOD and non-detects. Graduated symbology was used to visualize contaminant concentrations in QGIS version 3.12.

Map 1 shows hexavalent chromium concentrations detected in sampled wells in the study area. There were 13 sample sites with hexavalent chromium concentrations between 3.5ug/L – 10.4ug/L. At this concentration range, 7 (54%) sample sites were located <2 miles away from the center of the coal ash pond. 6(46%) sample sites were located >2 miles away from the center of the coal ash pond.

Map 2 shows barium concentrations detected in sampled wells in the study area. There were 13 sample sites with barium concentrations between 46.32ug/L – 340ug/L. At this concentration range, 1 (7.7%) sample site was located <2 miles away from the center of the coal ash pond. 12(92%) sample sites were located >2 miles away from the center of the coal ash pond.

Map 3 shows strontium concentrations detected in sampled wells in the study area. There were 13 sample sites with strontium concentrations between 135ug/L – 590ug/L. At this concentration range, 3(23%) sample sites were located <2 miles away from the center of the coal ash pond. 10(77%) sample sites were located >2 miles away from the center of the coal ash pond.

4. Discussion

In this study, we explored the makeup and quality of household water samples taken from private wells in Juliette, GA. We found that all samples taken contained concentrations of an array of metals determined to be of public health concern, including hexavalent chromium, lead, and selenium [27]. Given the spatial variation of well sampling locations, distance (miles) and elevation (feet ASL) were calculated for each observation. Previous evidence has shown that deposits of both natural and anthropogenic pollutants, including metals, can move through groundwater and permeate into aquifers that feed wells and springs [28]. We found that elevation and distance were negatively correlated ($\leq$-0.2) with a majority of the metal parameters, including hexavalent chromium. We also found that distance and elevation were significantly (p-value < 0.05) associated with reductions in hexavalent chromium, boron, cobalt, and strontium when linear regression was done. Generally, the majority of β-coefficients produced for metal parameters in linear regression models were negative.

Descriptive statistics found disparities in the variance of metal parameters in the dataset. This was due to either results being below the LOD or not having been tested for, or both. The homogeneity of some metal parameters resulted in zero and 'NA' values for standard deviation, kurtosis, skewness, and coefficient of variation that made it difficult to assess their true presence in water samples.

To measure the environmental and public health concern of detected metal contaminants in well water samples, results were compared to the EPA's National Primary Drinking Water Regulations (NPDWR). The NPDWR establishes maximum contaminant levels (MCL) for an array of natural and man-made contaminants, including inorganics, microorganisms, and disinfectants (EPA). The metal contaminants regulated by EPA's NPDWR evaluated in this study are arsenic, antimony, barium, beryllium, cadmium, lead, and selenium. Lead was the only contaminant that exhibited an observation (n = 1) over its MCL.

In this study, hexavalent chromium, aluminum, boron, cobalt, manganese, molybdenum, nickel, strontium, and vanadium are not federally regulated under the NPDWR. There is an MCL for total chromium under NPDWR of 100ug/L that does not distinguish between trivalent chromium (Cr3+) and hexavalent chromium (CrVI). CrVI is more toxic than Cr3+ and has been associated with birth defects and cancer at high doses and chromosomal damage in low-dose, chronic exposure [29].

The EPA sets unregulated National Secondary Drinking Water Regulation (NSDWR) MCLs (SMCLs) for contaminants determined to affect the appearance of drinking water (i.e. color, cloudiness) but do not pose a health risk to humans. SMCLs are not federally enforceable and, therefore, do not require monitoring unless individual state governance mandates it. In this study, aluminum, manganese, and zinc are part of the NSDWR. The secondary MCLs for aluminum, manganese, and zinc are 50 – 200 ug/L, 50 ug/L, and 5000 ug/L, respectively.

Correlation is a statistical method for assessing the linear relationship between two continuous variables where the strength of the association can fall anywhere between -1 and +1. In this study, we were most interested in the correlation between spatial and metal parameters. Neither elevation nor distance had positive correlations with metal parameters ≥0.20. Elevation exhibited low negative correlations (≤-0.30) with boron and strontium, indicating that increases in elevation coincide with decreases in boron and strontium, individually. Distance exhibited low negative correlation with cobalt, indicating that increases in distance coincide with decreases in cobalt concentrations in ground water. Negative correlations with elevation in this study may indicate that the underlying regional geology at higher elevations does not retain some naturally occurring elements such as strontium and boron, while a negative correlation with distance may indicate that some contaminants are not moving through the environment as readily.

Linear regression of spatial predictor variables on metal outcome variables found that the consistent relationships between distance and elevation were associated in a negative direction with metal concentration. Such a relationship is aligned with the a priori hypothesis that concentrations of metals would be greatest nearest to the potential source, in this case, the Planta Scherer ash pond, and decrease with increasing distance from that source. The relationship to elevation also suggests that specific geology at various elevations may impact dispersion of the contaminants from the source.

Spatial mapping of sampled well locations and their associated concentrations of hexavalent chromium, barium, and strontium found that half of them were between 2-4 miles from the center of the Plant Scherer coal ash pond. The center of the pond was calculated using the QGIS polygon centroid tool. The majority (62%) of wells found to contain hexavalent chromium concentrations in the upper threshold (3.52 – 10.4 ug/L), were located northeast of the center of the coal ash pond. Over half (54%) of wells found to contain barium concentrations in the upper threshold (46.32 – 340 ug/L), were also located northeast of the center of the coal ash pond. 69% of wells found to contain strontium concentrations in the upper threshold (135 – 590 ug/L) were located northeast of the center of the ash pond as well. The spatial similarities found could be due to sampling bias as nearly half (47%) of the sampled wells are located northeast of the ash pond center.

Data that contained many data points that were either below the LOD or were not tested for, or both, limited this study. The lack of heterogeneity and variance in the dataset made it difficult to explore associations between variables and required that we remove some variables altogether. For example, many of the contaminants regulated by the EPA's NPDWR such as arsenic and cadmium were not included in our analysis. Another limitation of this study is the opportunistic nature of the sampling methods and timeline. Convenience sampling of household wells is a fast, simple, and cheap method of sample collection. However, convenience sampling often does not produce representative results and can be difficult to replicate. This limitation is further evidenced from single samples taken from one point in time over the course of a 13-month time period. Confounding variables such as weather and household drinking water behaviors (i.e. use of a filter or bottled water) were also not examined in this study. Finally, other spatial and water characteristics specific to sampled wells such as well depth and pH were not examined.

The public health impact of this study will be to inform the Juliette, GA community and local public health and environmental advocacy groups as they continue to try and understand the nature and extent of metal contamination in drinking water sources and explore solutions. This study will help to increase awareness and knowledge of the community for further engagement and public health action.

5. Conclusion and recommendations

In conclusion, we have found that increasing sampled well distances from the center of the Plant Scherer coal ash pond are significantly associated with decreases in some metal contaminants. This result may be suggestive of the coal ash ponds as a potential source of contamination, given the consistent decreases in concentration for a number of contaminants, including Al, Cr(VI), and Co. This study is the first exploration of drinking water quality sampled from private wells in Juliette and their spatial association to a nearby coal ash impoundment. Continued, routine drinking water sampling at households located within a 4-mile radius of the coal ash pond may provide more evidence of metal pollution in area wells. Further studies are needed to explore the origins and extent of metal contamination in groundwater and drinking water wells in Juliette, GA and how they related to the presence of Plant Scherer's coal ash pond.

Tables and Figures

Table 1. Metal parameter summary statistics with comparison to EPA drinking water standards (*n*=64). All parameters are shown in ug/L.

										EPA	**Number of values exceeding standard limit**
Parameters	**Range**	**Mean**	**Median**	**SD**	**Kurtosis**	**Skewness**	**Coefficient of Variation**	**Values below LOD**	**Values not tested**	**MCL**	**EPA MCL**
Cr(VI)	0.00071 – 10.4	1.91	0.88	2.49	3.5	1.9	1.3	10	0	100[1]	0
Al	11 – 230	23.1	14.1	36.1	18	4.3	1.6	57	0	50 – 200	4 (6.3%)
As	5.7	5.7	5.7	0	NA	NA	0	64	0	10	0
Sb	5.7	5.7	5.7	0	NA	NA	0	15	49	6	0
Ba	0.71 – 340	40.85	23.7	56.8	12	3.1	1.39	10	5	2000	0
Be	0.21	0.21	0.21	0	NA	NA	0	20	44	4	0
B	2.1 – 96.7	6.7	0.21	17.6	14	3.8	2.6	55	5	NA	NA
Cd	0.71	0.71	0.71	0	NA	NA	0	20	44	5	0
Co	1.41 – 10	1.74	1.41	1.52	19	4.5	0.87	61	0	NA	NA
Pb	1.8 – 30	7.45	7.07	3.06	45	6.5	0.41	61	0	15	1 (1.6%)
Mn	0.71 – 861	29.72	0.71	116.07	40	6.1	3.91	46	0	50	9 (14%)
Mo	2.8	2.8	2.8	0	NA	NA	0	15	49	NA	NA
Ni	3.5	3.5	3.5	0	NA	NA	0	11	53	NA	NA
Se	14	14	14	0	NA	NA	0	64	0	50	NA
Sr	0.21 – 590	105.95	74.4	98.85	8.8	2.6	0.93	2	5	NA	NA
V	2.12 – 34.7	6.2	2.61	5.94	7.4	2.3	0.96	32	0	NA	NA
Zi	1.4 – 38.4	5.1	1.4	11.7	5.1	2.7	2.3	9	54	5000	0
Sulfate	14.1 – 369000	17935.9	2700	52867.8	35	5.7	2.9	17	10	250000	1 (1.6%)

[1] 100 ug/L is the MCL for total chromium

Table 2. Spatial parameter summary statistics. Elevation is shown in feet ASL. Distance is shown in miles. (*n* = 64)

Parameters	Range	Mean	Median	SD	Kurtosis	Skewness	Coefficient of Variation
Elevation	339.45 – 616.53	466.27	463.35	60.06	-0.1	0.24	0.13
Distance	0.63 – 7.57	2.79	2.75	1.41	1.1	0.93	0.51

Table 3. Pearson correlation matrix (*n* = 64)

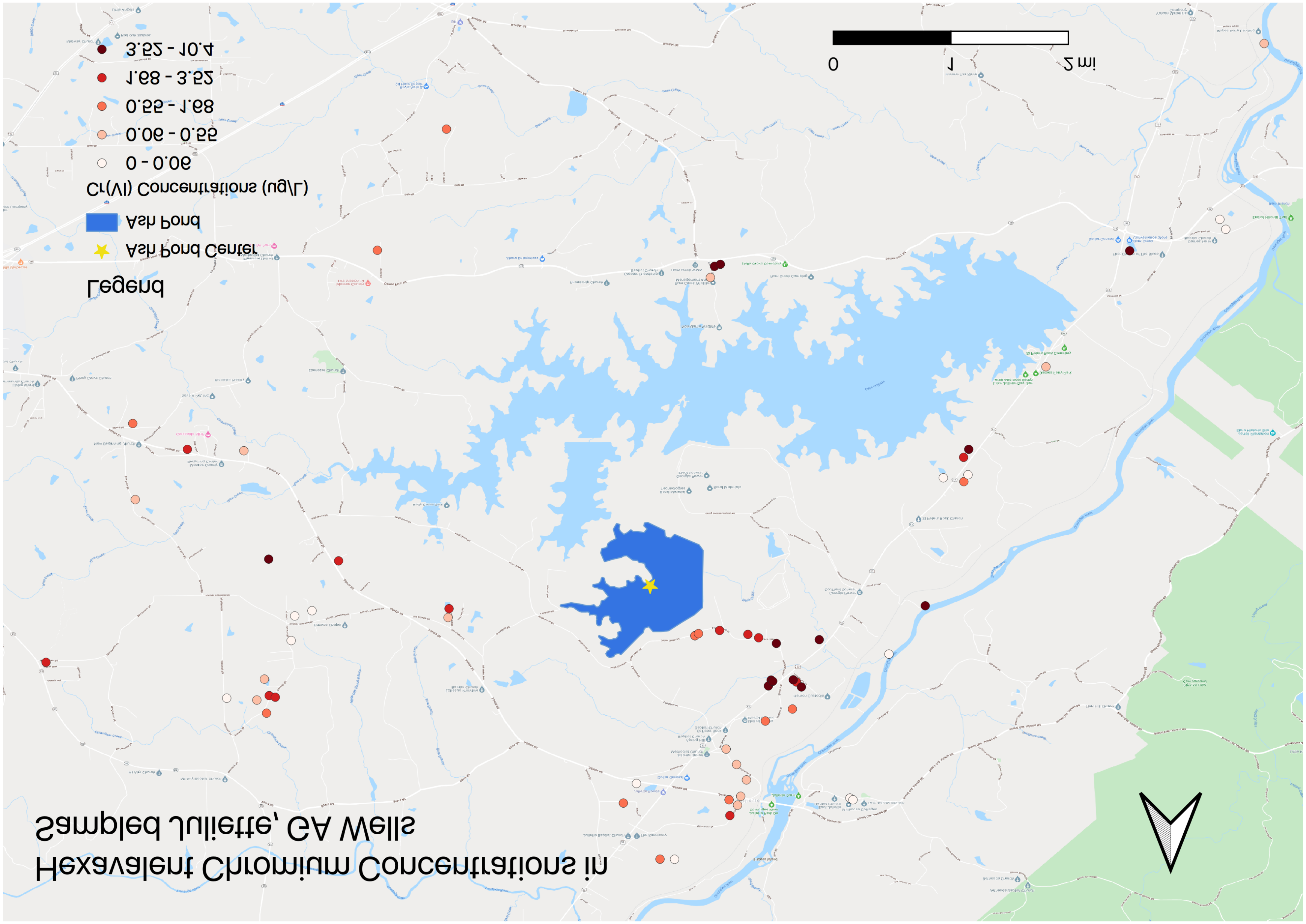
Parameter	Elevation	Distance	Cr(VI)	Al	Ba	Bo	Co	Pb	Mn	St	Sulfate	V
Elevation	1											
Distance	0.22	1										
Cr(VI)	-0.27	-0.22	1									
Al	-0.27	-0.16	-0.005	1								
Ba	-0.11	-0.05	-0.08	0.03	1							
B	-0.35	0.004	-0.09	0.31	-0.03	1						
Co	0.08	-0.34	-0.03	-0.05	-0.06	0.36	1					
Pb	0.05	-0.07	-0.09	-0.03	-0.04	-0.01	0.41	1				
Mn	-0.12	0.2	-0.18	0.04	-0.08	0.19	0.06	0.28	1			
Sr	-0.42	0.16	-0.16	0.10	0.25	0.26	-0.12	0.005	-0.0008	1		
Sulfate	-0.07	-0.2	-0.07	-0.05	-0.09	-0.02	-0.07	-0.04	0.005	0.03	1	
V	-0.11	-0.11	0.65	-0.02	-0.14	-0.12	-0.11	-0.02	-0.16	-0.12	-0.06	1

Table 4. Regression analysis summary for distance and elevation predicting metal contamination in wells (*n* = 64)

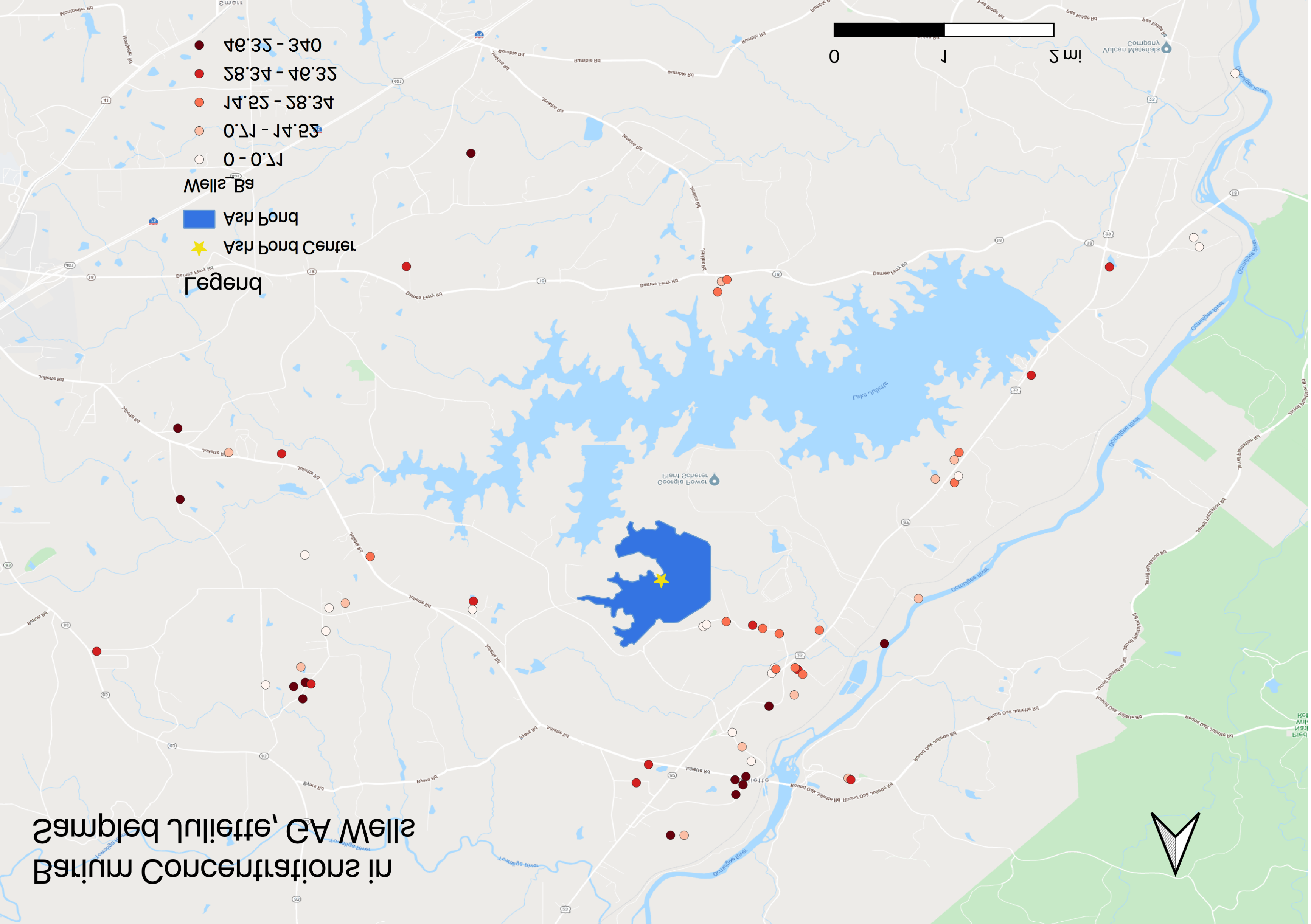
	Distance (Mi)			**Elevation (Ft ASL)**		
Parameter	**β**	**Standard Error**	***p***	**β**	**Standard Error**	***p***
Cr(VI)	-0.38	0.22	0.08	-0.01	0.005	0.03*
Al	-35.17	20.05	0.08	0.03	0.48	0.95
Ba	-2.15	5.41	0.69	-0.10	0.12	0.41
B	0.05	1.68	0.98	-0.10	0.04	0.006**
Co	-0.36	0.13	0.007**	0.002	0.003	0.52
Pb	-0.15	0.27	0.59	0.002	0.006	0.72
Mn	16.65	10.21	0.11	-0.23	0.24	0.36
Sr	11.62	9.3	0.21	-0.69	0.2	0.0009***
Sulfate	-7899	5347	0.14	-64.94	120.34	0.592
V	-0.48	0.53	0.37	-0.01	0.01	0.39

*p-value < 0.05, **p-value < 0.01, ***p-value < 0.001

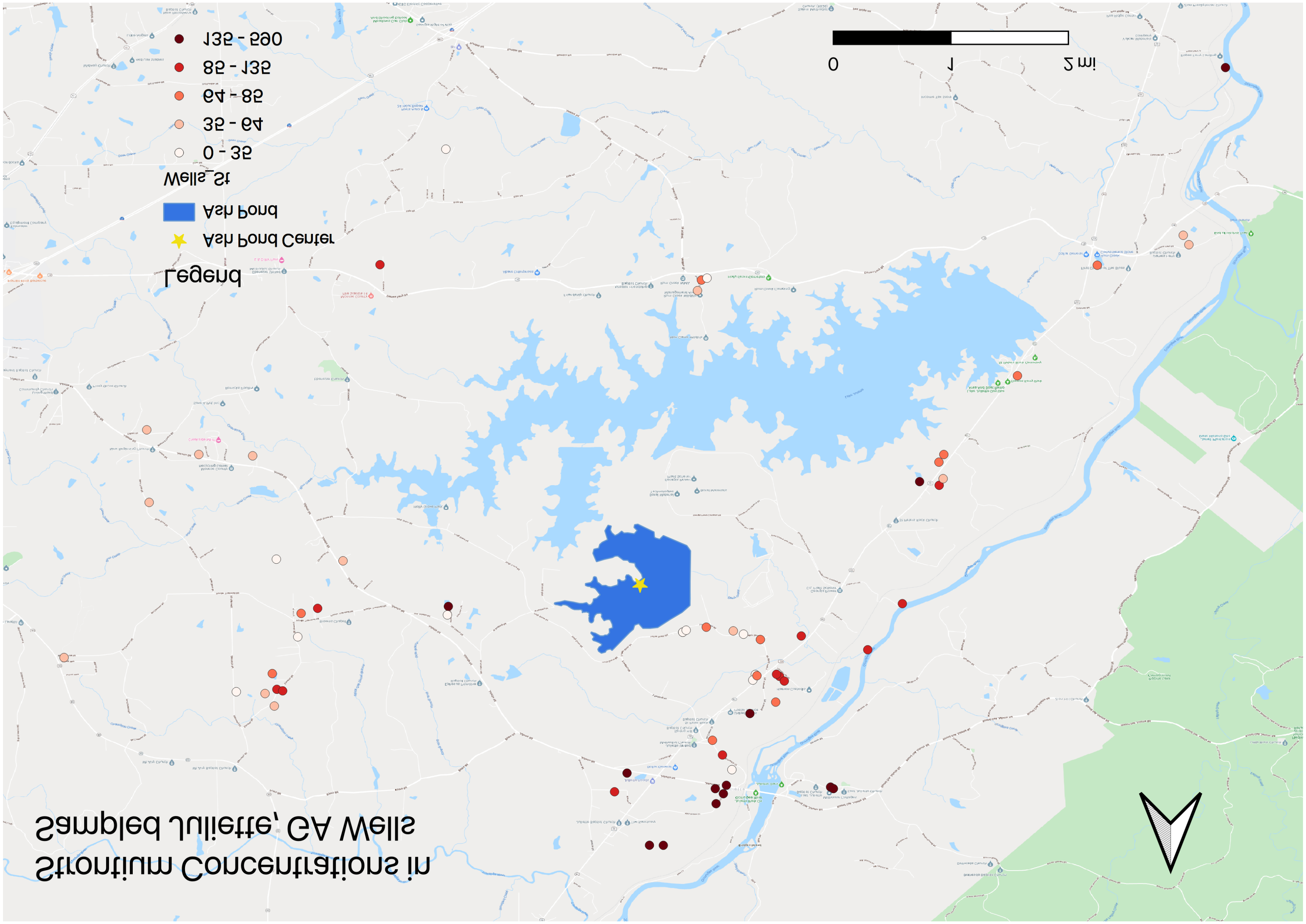
Map 1. Hexavalent chromium concentrations in sample wells (*n*=64).



Map 2. Barium concentrations in sample wells (*n*=64).



Map 3. Strontium concentrations in sample wells (*n*=64).



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