Water Quality Study at the Pauli Murray Center in Durham, North Carolina

by Ryan Parks

Advisors: Dr. Joel Meyer and Dr. Ryan Emanuel

April 28, 2023

Master’s project submitted in partial fulfillment of the requirements for the Master of Environmental Management degree in the Nicholas School of the Environment of Duke University
Executive Summary

This study investigated the potential impact of Maplewood Cemetery on the groundwater quality at the Pauli Murray Center for History and Social Justice (PMC), located in the West End neighborhood of Durham, North Carolina. The PMC, a human rights nonprofit organization operating out of the childhood home of the renowned activist Pauli Murray, is located directly downhill from Maplewood Cemetery, a burial ground originally designated for white individuals only. In Pauli Murray’s book *Proud Shoes: The Story of An American Family*, the cemetery’s problematic relationship to Murray’s childhood home is described in terms of surface water damage to the property and drinking water well.

While Murray’s historical account of the harm inflicted by the cemetery portrays surface water damage to their drinking water well, it is unclear if the cemetery contaminated the well water at the aquifer, or groundwater, level. Prior research indicates a noticeable impact that cemeteries have on nearby groundwater quality, prompting our inquiry into the groundwater quality at the PMC. In assessing the groundwater underlying the PMC and cemetery, we sought to characterize the current i) direction and rate of groundwater flow and ii) water quality to comprehend the legacy of potential groundwater contamination occurring when residents were accessing groundwater in the early 1900s.

We worked with an environmental engineering firm to develop three monitoring wells—one within Maplewood Cemetery and two on the PMC property. The well in the cemetery was a shallow well while the PMC contained one shallow well and one deeper well. Field survey
measurements were performed, and water samples were collected from the three monitoring wells and a nearby stream from September 2022 to December 2022.

**Direction and Rate of Groundwater Flow.** Our field survey measurements and extrapolated estimates from relevant hydrogeologic literature indicate that groundwater flows from the cemetery to the PMC in a matter of years, although the exact time frame remains uncertain. **Metals.** Certain metals, such as lithium, manganese, arsenic, lead, and aluminum, were found in concentrations exceeding non-enforceable water quality standards like the North Carolina Groundwater Standards. No measured concentrations of metals exceeded enforceable drinking water standards. The confined aquifer (PMC-2) generally displayed the highest metal concentrations of the three monitoring wells. Concentrations of these metals were typically higher in the cemetery well than in the shallower well at the PMC, both of which tapped into the same surficial aquifer. Furthermore, the water chemistry of the shallow and deep aquifers suggests a connection between the groundwater at the cemetery and the shallow groundwater at the PMC. **Bacteria.** Total coliform concentrations in all three monitoring wells and the stream exceeded the EPA's Total Coliform Rule, with levels two-to-five times higher in the cemetery than at the PMC. The stream contained the highest total coliform concentrations and was the only source with detectable levels of *Escherichia coli*, a specific type of coliform bacteria. While total coliforms alone do not confirm the presence of harmful bacteria, they can provide insight into the presence and concentrations of pathogenic bacteria in the surficial and confined aquifers at this site.

Differences in metal concentrations between the monitoring wells and the stream may be attributed to varying sources of potential contamination or geochemical processes, such as dissolution, precipitation, adsorption, and desorption of metals and bacteria onto minerals and organic matter. Cemetery-related activities and contamination from nearby industrial sources could also be contributing factors.

Our work was consistent with Murray’s observations regarding the cemetery's threat to the PMC. Moreover, the apparent connection between the shallow aquifers at the PMC and the cemetery implies that the City of Durham's 2014 drainage efforts addressing surface water flow would not eliminate the potential transport of contaminants from the cemetery to the PMC and the surrounding West End neighborhood. To conclusively determine the source of the metals and bacteria mentioned in this study, further investigation is required, including examining a nearby reference site, and conducting more robust geochemical and microbiological tests. This study contributes to the environmental justice literature by shedding light on a potential environmental hazard affecting a community of color.
# Table of Contents

1. Introduction .................................................................................................................. 1
   1.1 West End Neighborhood in Durham, North Carolina ............................................. 1
   1.2 Previously Studied Impacts of Cemeteries on Groundwater Quality ....................... 4
      1.2.1 Human Decomposition and Leachate .......................................................... 4
      1.2.2 Metals in Groundwater ................................................................................. 5
      1.2.3 Bacteria in Groundwater .............................................................................. 5
   1.3 Setting ....................................................................................................................... 5
      1.3.1 Geology .......................................................................................................... 5
      1.3.2 Hydrogeology ............................................................................................... 6
      1.3.3 Climate .......................................................................................................... 6

2. Methods ......................................................................................................................... 6
   2.1 Monitoring Well Construction and Sampling .......................................................... 6
      2.1.1 Metals ............................................................................................................ 7
      2.1.2 Bacteria ....................................................................................................... 7
   2.2 Hydraulic Gradient and Groundwater Flow ............................................................ 8

3. Results ........................................................................................................................... 8
   3.1 Hydraulic Gradient ................................................................................................. 8
      3.1.1 Rate of Water Flow ....................................................................................... 9
   3.2 All Metals ................................................................................................................ 10
      3.2.1 Trace Metals ............................................................................................... 10
   3.3 Bacteria .................................................................................................................... 12
   3.4 Drinking Water Health Standards ......................................................................... 12
      3.4.1 Metals .......................................................................................................... 12
      3.4.2 Bacteria ...................................................................................................... 13

4. Discussion ...................................................................................................................... 14
   4.1 Hydraulic Gradient and Groundwater Flow ........................................................... 14
   4.2 Metals ...................................................................................................................... 14
   4.3 Bacteria .................................................................................................................... 15
   4.4 North Carolina Groundwater .................................................................................. 15
   4.5 Comparison of Other Cemetery Groundwater ...................................................... 16
      4.5.1 Metals .......................................................................................................... 16
      4.5.2 Metals .......................................................................................................... 16

5. Takeaways .................................................................................................................... 16

6. Conclusion ..................................................................................................................... 17

7. Bibliography .................................................................................................................. 18
Abstract
This project examined Maplewood Cemetery's effects on the groundwater quality of the Pauli Murray Center for History and Social Justice (PMC). Maplewood Cemetery and the PMC are located in the West End neighborhood of Durham, North Carolina, a prominent and historic African American neighborhood. The PMC bridges history and human rights by honoring Pauli Murray's lifelong fight for peace and equity. At the heart of the PMC rests Pauli Murray's childhood home. This home is situated directly behind Maplewood Cemetery, created as a white-only burial ground. Based on literature examining the effects of cemeteries on groundwater quality, we hypothesized that Maplewood Cemetery might negatively affect the groundwater beneath the PMC. Water samples were collected from three monitoring wells—one at Maplewood Cemetery and two on the premises of the PMC—and a nearby stream from September 2022 to December 2022. Water samples were tested for thirty-three metals and total coliform bacteria. Lithium, manganese, arsenic, lead, and aluminum concentrations in the three monitoring wells and the stream exceeded various non-enforceable water quality standards, such as the North Carolina Groundwater Standards, but did not exceed enforceable drinking water standards. The concentrations of certain metals were generally higher in the samples collected from the well in the cemetery compared to the shallower well at the PMC, which tapped into the same surficial aquifer as the cemetery well. Total coliform concentrations in the three monitoring wells and the stream exceeded the EPA's Total Coliform Rule, and the cemetery had two-to-five-fold higher levels than the PMC. The stream had ten-to-thirty-fold higher total coliforms than the PMC and was the only water source that contained detectable levels of Escherichia coli, a type of coliform bacteria. Further investigation into a reference site and geochemical tracing is needed to determine whether the measured metals and bacteria naturally occur or derive from anthropogenic processes relating to the human burial process. This study contributes to the environmental justice literature regarding disproportionate environmental hazards in communities of color.

1. Introduction

1.1 West End Neighborhood in Durham, North Carolina

The Pauli Murray Center for History and Social Justice (PMC) is a nationally significant historical site located in the West End neighborhood of Durham, a city in the Piedmont region of North Carolina. The PMC bridges history and human rights by honoring Pauli Murray’s lifelong fight for peace and equity. Rev. Dr. Pauli Murray was a Black activist, feminist, LGBTQIA+ advocate, lawyer, priest, and poet (Rosenberg, 2020). Pauli Murray's childhood home, built in 1898, is at the heart of the Center (The Pauli Murray Center for History and Social Justice, 2022). This home is situated directly downhill from Maplewood Cemetery, created as a white-only burial ground, and recognized as Durham’s very first public space (Anderson, 2011). The portion of Maplewood Cemetery closest to
Murray’s home was developed several years after Murray’s family (and other families) had established their residence (Murray, 1978). Pauli’s grandfather, Richard Fitzgerald, had an option from the City of Durham to use the land behind their home (now the PMC) for farming and brickmaking. However, the city canceled this option when they began developing the portion of the cemetery that ends less than 5 meters from the PMC (Murray, 1978). The cemetery’s development was a source of disapproval for many residents of the West End—a historically African American working-class neighborhood (Brown, 2008). Accounts from Pauli Murray’s book, Proud Shoes: The Story of An American Family, portray the problematic relationship that Maplewood Cemetery posed on Murray’s family home and the family’s wellbeing.

At times the cemetery was like a powerful enemy advancing relentlessly upon us, pushing us slowly downward into the Bottoms. Indeed, some of its death and decay had already encroached upon us. Grandfather’s crib and stable, which hugged the cemetery fence, had sunk into a marsh of standing water. The well shed had rotted and I could look through a gaping hole in the latticework and see the oily green scum of water below the crumbling floorboards. That well was a childhood terror…The cemetery was looked upon us as an intruder by our family, and Grandfather had battled against it for years before it got the upper hand…My family could remember the time when the hillside behind our house was a meadow and wheat field skirted by a forest of oaks, pines, cedars and sassafras bushes. Grandfather had an option from the city to dig clay from part of the land [for brickmaking] and farm the rest. The trouble started when the city decided to extend Maplewood Cemetery east of Chapel Hill Road and canceled Grandfather’s option…Before that time, he had had difficulty protecting his own land from the underground springs which bubbled up on the city’s side of the line, but he had handled the problem by digging a four-foot ditch on his side to drain the water northward to a stream and putting up a wooden fence between himself and the city to protect his ditch. Now the city’s workmen began making a roadway on the city’s side of the line and knocked down Grandfather's fence. They threw wagonloads of dirt over the line and filled his ditch. Water powered down the hill into our yard. Grandfather had his ditch reopened at his own expense and warned the city, but the careless workmen ignored him and kept right on refilling the ditch…He went from city official to another and got nothing but shrugs and stares. He then hired a lawyer and sued the city for damages. Nothing came of it. A local newspaper reported derisively that a blind old colored man on the outskirts of town was stubbornly trying to prevent the city’s development but had little chance of success. Grandfather was so humiliated and so feeble by then that he dropped the suit, but Grandmother refused to be silenced…The forest was cut down, and the tombstones began to march down the hill toward our back door. As the graves crept closer and the water from decomposed bodies drained over our property, our well was condemned. For a long time the family had to carry water by hand from a great distance until money could be scraped together to install city water…We were seldom free from the sickening odor of standing water and rotting weeds. Our yard was crisscrossed with tiny ditches to get rid of it but we never entirely succeeded. Of course, the city never paid Grandfather a cent for any damage (Murray, 1978, pp. 28-29).

This block quote paints a picture of the harm—psychosocial distress, property damage, and surface water contamination—that the cemetery inflicted on Pauli’s family in the 1880s. For
decades, members of Murray’s family appealed to city officials for the redress of the surface water flowing from the cemetery that was ruining their home (P. F. Dame, personal communication, December 6, 1934). It was not until 2014 (130 years later) that the City of Durham responded to requests—by current staff members of the PMC—to address the damaging surface water by constructing a drainage system behind the PMC to divert water away from the house. This drainage system is depicted in Figure 1A (Lau, 2022). Figure 1A also illustrates the property damage of Murray’s childhood home caused by surface water runoff from the cemetery. The eroding chimney in between what is now the back part of the house and the city drainage system is evidence of a previously existing portion of the house, whose foundation was deteriorated by surface water runoff from the cemetery (Lau, 2022). The West End neighborhood started using piped water from the City of Durham in the early 1900s, according to a city-maintained webpage advertising a current water rehabilitation project in the West End (City of Durham, 2022). Thus, residents of the West End were using well water that, based on the fact that the well was condemned, was likely contaminated by surface water flowing from the cemetery, for over a decade.

While Murray’s historical account—conveyed in the aforementioned block quote—depicts surface water contamination of their family well, it is unknown whether contamination occurred at the aquifer level. Furthermore, it is uncertain if there was or is any interaction between the groundwater at the cemetery and the groundwater at the PMC. To explore these uncertainties, we aimed to assess the potential impact that the cemetery has or may have had—at the aquifer level—on its groundwater and the PMC’s groundwater. To assess this impact, we sought to characterize current levels of contamination and, as much as possible, shed light on the legacy of contamination that the West End neighborhood faced in the years between the late 1800s and early 1900s, when residents could have been exposed to harmful constituents in their water due to the proximity of Maplewood Cemetery. There is likely no present public health threat pertaining to groundwater in the West End neighborhood, as to our knowledge, the groundwater has not been used for drinking or other purposes in over a century.
1.2 Previously Studied Impacts of Cemeteries on Groundwater Quality

1.2.1 Human Decomposition and Leachate

Cemeteries may be anthropogenic sources of water contamination in urban areas (Żychowski & Bryndal, 2015). In the process of human decomposition, 1 kilogram of body weight produces 0.4 to 0.6 liters of leachate (Silva, 1995). This leachate, which is a contaminated liquid created by water percolating through and extracting soluble or suspended components of human bodies, contains approximately 10% organic substances, 30% salts (in the form of ions with phosphorous, nitrogen, chloride, Na⁺, Ca²⁺, HCO₃⁻, and metal compounds including chromium, lead, and manganese), and 60% water (Weaver et al., 1998; Żychowski & Bryndal, 2015). This leachate can include chemical substances used in chemotherapy and embalming processes (arsenic, formaldehyde, and methanol), personal care products (e.g., cosmetics containing phthalates and parabens), and other components involved in the internment process like paint or coffin varnishes (including arsenic and mercury) (Fiedler et al., 2012; Silva & Malaguti Filho, 2012; Matos, 2001). This leachate may also contain pathogenic bacteria deriving from human decomposition, such as *Staphylococcus aureus* and *Clostridium perfringens*. Moreover, the presence of indicator bacteria, such as total coliforms, may demonstrate that leachate bacteria derive from human intestines (Trick et al., 2001).
1.2.2 Metals in Groundwater

Human burials have, in some cases, been found to lead to the higher-than-normal presence of zinc, barium, calcium, sodium, arsenic, manganese, aluminum, boron, titanium, cobalt, nickel, copper, lead, iron, and chromium in and around cemeteries (Feidler, 2012; Brennan et al., 2018; Jonker & Oliver, 2012; Spongberg & Becks, 2000). The study that focused on zinc, barium, calcium, and sodium occurred in a cool, humid climate, with underlying red Triassic sandstone regolith and Anthrosols soil. The site of this same study had a strong lateral flow that led to moistness in the soil (Feidler, 2012). The studies that focused on arsenic, manganese, aluminum, boron, titanium, uranium, cobalt, and nickel did not include a hydrogeological characterization of their test site (Brennan et al., 2018; Jonker & Oliver). The study that looked at copper, lead, iron, and chromium took place in an area with Del Rey silt loam (low permeability and runoff) and Shoals silt loam (moderate permeability, very slow runoff) (Spongberg & Becks, 2000).

1.2.3 Bacteria in Groundwater

Higher levels of biological groundwater contamination are associated with warmer and moister climates (Żychowski & Bryndal, 2015). High levels of bacteria, namely thermotolerant coliforms, fecal streptococci, and *Staphylococcus aureus*, have been found in groundwater in and near cemeteries that experienced long-lasting rainfall periods (Trick et al., 2001). Researchers also note that geology, sorption capacity, and groundwater circulation influence bacteria transport, particularly for cemeteries situated on slopes (Żychowski & Bryndal, 2015).

1.3 Setting

1.3.1 Geology

Located in the Piedmont physiographic province of North Carolina, the West End neighborhood lies within the Durham-Sanford sub-basin of the Triassic Basin. The underlying sedimentary rock formations in the Triassic Basin primarily consist of clay-rich sandstone, siltstone, and mudstone (LeGrand, 1979). These rocks are unevenly distributed and poorly sorted, resulting in limited pore spaces for water storage and restricted water mobility (Bain & Harvey, 1977; LeGrand, 1979). A layer of regolith, which includes the soil zone and a partially weathered, decomposed bedrock called saprolite, covers the bedrock. Saprolite forms through the physical and chemical weathering processes of bedrock and varies in composition from clay to granular particles as large as boulders. It often retains the texture of the original rock from which it derives (Bain & Harvey, 1977; Parker, 1979; LeGrand, 2004).

The soils overlaying the Triassic sedimentary rock formations are composed of silty clays and sandy clays, which have strong cohesiveness that decreases closer to the surface (Hoffman & Gallagher, 1989). These clay-rich soils gradually transition into fine-grained sandy silts and silty sands near the surface (Rix, 2006; Hencher & McNicholl, 1995). Soils derived from Triassic basin sedimentary rock near the surface consist of clay loam (35-53 inches below the surface), clay (6-35 inches below the surface), and sandy loam (0-6 inches below the surface) (Soil Survey Staff, 2022). The Maplewood Cemetery is underlain by White Store sandy loam soil, while the PMC and stream areas consist of White Store Urban-Land complex soil. These White Store soils contribute to moderate drainage and very high runoff throughout the study area (Soil Survey Staff, 2022; Gabryś & Kordan, 2013).
1.3.2 Hydrogeology

The groundwater system in the Piedmont region generally comprises a two-part system—saprolite and underlying bedrock—with the saprolite serving as the predominant reservoir for the underlying bedrock (LeGrand, 2004; Heath, 1980). When rainfall infiltrates the regolith, it reaches the saturated zone, which is often located within the saprolite, where it accumulates as groundwater within pore spaces. At numerous locations in the Piedmont region, the regolith encompasses a transitional area between saprolite and fractured bedrock. This zone comprises large, partially weathered bedrock and a smaller amount of saprolite (Daniel & Dahlen, 2002).

1.3.3 Climate

The average annual temperature in Durham, North Carolina, is 59° Fahrenheit, with an average temperature of 70° Fahrenheit from May to October, and an average temperature of 46° Fahrenheit from November to April (NOAA). The climate of North Carolina is considered moist, with very warm summers (Kunkel et al., 2020). During the summer, Durham is also considered muggy, with humidity reaching 82% in July (NASA, 2022). Additionally, North Carolina receives a relatively high volume of rain; it ranks ninth out of the fifty states that receive the most rainfall. Precipitation is the primary source of groundwater recharge and averages 2.5 – 5 inches per month in the Piedmont region (LeGrand, 2004; NOAA).

2. Methods
2.1 Monitoring Well Construction and Sampling

![Figure 1B: Testing Site Overview](image-url)
To assess the impact that the cemetery has on its groundwater and the PMC’s groundwater at the aquifer level, we developed three monitoring wells to i) determine the direction and rate of groundwater flow between the cemetery and PMC, and ii) measure collected water samples for contaminants: metals and coliform bacteria. Innovative Environmental Technologies Inc. installed three monitoring wells on the premises of the PMC and the Maplewood Cemetery in the West End neighborhood using a mechanical auger and air rotary drilling equipment. The wells were constructed in adherence to the standards and regulations of the North Carolina Department of Environmental Quality Division of Water Resources (North Carolina Department of Environmental Quality Division of Water Resources, 2019). Two monitoring wells were strategically placed on the grounds of the PMC, while a third monitoring well was positioned upslope, approximately 141 feet away, within Maplewood Cemetery. The wells located at the PMC are denoted as PMC-1 and PMC-2. PMC-1, with a depth of 32 feet, accesses the surficial aquifer, while PMC-2 penetrates the confined aquifer at a depth of 47 feet. The monitoring well in Maplewood Cemetery is designated as C-1, which extends 51 feet deep and taps into the surficial aquifer (Figure 1B). The arrangement of these monitoring wells enables the estimation of the local water table gradient and potential vertical exchange between the water table and confined aquifer. The stream was included in our testing to inform the potential interaction between the surface water and groundwater in this area and to compare the concentrations of target metals and bacteria between the two water sources.

Water samples were collected from the monitoring wells and the stream from September 2022 to December 2022. There were four individual sample collections: September 2, September 23, October 28, and December 2. Water samples were collected using 100% virgin fluorinated ethylene propylene (FEP) disposable, sterile bailers in accordance with the USGS National Field Manual (Pine Environmental, 2019; United States Geological Survey, 2006). In order to obtain water samples that were representative of natural groundwater conditions, each of the monitoring wells was purged, or flushed, of water volume equal to three times the well volume prior to collection. The cone of depression that was created from the well purging instigated recharge from adjacent groundwater. This recharge represented the ambient groundwater conditions. The depth to water of the three wells was measured each collection session before purging using a Geotech portable water level meter. Sample collection commenced once the field parameters (pH, specific conductivity, Dissolved oxygen (DO), and temperature) were documented on the YSI ProfessionalPlus multiparameter probe. Field survey measurements were cataloged using a CST/Berger electronic self-leveling rotary laser.

2.1.1 Metals

Samples were strained through a 0.45 micron (μm) filter into acid-washed HDPE bottles and acidified in the field to pH < 2. Water samples were stored in a laboratory refrigerator and analyzed at Duke University. Trace metal concentrations were measured using a VG PlasmaQuad-3 inductively coupled plasma mass spectrometer (ICP-MS) and calibrated to the National Institute of Standards and Technology 1643e standard in the Vengosh Lab at Duke University (Coyte et al., 2020).

2.1.2 Bacteria
Bacteria samples were transported to Duke University no more than twenty-four hours after collection. Samples were prepared with IDEXX Colilert reagent, sealed in a Quanti-Tray, incubated at 35°C for twenty-four hours, and analyzed using a most probable number (MPN) table (IDEXX, 2022).

2.2 Hydraulic Gradient and Groundwater Flow

We focused on the relationship between well C-1 and well PMC-1 since these wells tap into the same surficial aquifer and serve as more accurate references to each other than well PMC-2, which taps into a different (confined) aquifer. The heights above sea level of PMC-1 and C-1 and their respective water depths were documented during each collection session. To determine the direction of groundwater flow at our site, we calculated the hydraulic gradient. We first determined the average water depths of C-1 and PMC-1 with respect to their elevations above sea level. Then, we computed the difference in their water depths and divided this value by the horizontal distance between the two wells. This calculation provided us with the hydraulic gradient, which indicates the direction of groundwater flow within the surficial aquifer.

\[
\text{Hydraulic Gradient} = \Delta \text{height} / \Delta \text{length}
\]

We extrapolated known hydraulic conductivity and porosity values for saprolite, which is the predominant groundwater reserve found in the sedimentary Triassic sections of the Piedmont region (Daniel & Harned, 1998). By applying Darcy's law and a fundamental velocity equation for groundwater flow (Heath, 1980; Schaeffer, 2019), we were able to estimate the rate of groundwater movement beneath the PMC and cemetery. It is important to note that hydraulic conductivity and porosity values vary by orders of magnitude, even within the same region; therefore, calculated values are order-of-magnitude estimates. The values we borrowed from the work of Heath 1980 and Schaeffer 2019 serve as approximate estimations of groundwater flow.

\[
\text{Darcy’s Law} \quad q = -K \cdot (\Delta h / \Delta l)
\]

\[
\text{Velocity} \quad V = q / \Phi
\]

3. Results

3.1 Hydraulic Gradient

<table>
<thead>
<tr>
<th>Date</th>
<th>PMC-1</th>
<th>PMC-2</th>
<th>C-1</th>
<th>Hydraulic Gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/2/22</td>
<td>3.40</td>
<td>2.79</td>
<td>6.91</td>
<td>0.058018605</td>
</tr>
<tr>
<td>9/23/22</td>
<td>3.66</td>
<td>2.92</td>
<td>13.18</td>
<td>-0.081976744</td>
</tr>
<tr>
<td>10/28/22</td>
<td>3.45</td>
<td>8.10</td>
<td>7.06</td>
<td>0.055655814</td>
</tr>
<tr>
<td>11/11/22</td>
<td>3.56</td>
<td>8.13</td>
<td>7.32</td>
<td>0.052111628</td>
</tr>
<tr>
<td>Average</td>
<td>3.52</td>
<td>5.49</td>
<td>8.62</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 2A: Water depths of the 3 wells before each sample collection and hydraulic gradients between C-2 and PMC-1
According to our field survey measurements, C-1 is situated at an elevation of 119 meters above sea level, while PMC-1 is at an elevation of 113 meters above sea level. The distance between C-1 and PMC-1 is 43 meters. We calculated hydraulic gradients from the four collection periods. We then averaged the four hydraulic gradient values to obtain an average hydraulic gradient of 0.02, or 2%. An average hydraulic gradient of 0.02 signifies that, from September 2022 to December 2022, the groundwater at our site flowed from the cemetery toward the PMC.

![Figure 2C: Cross-section of testing site](image)

### 3.1.1 Rate of Water Flow

The median value for hydraulic conductivity in the saprolite of the sedimentary Triassic sections of the Piedmont region is $1 \times 10^{-6}$ m/s (Schaeffer, 2019). The average saprolite porosity ($\Phi$) in the Piedmont region is 25% (Heath, 1980). Plugging in our extrapolated hydraulic conductivity and porosity values into Darcy’s law and velocity equation yielded an estimated groundwater flow of approximately $7 \times 10^{-3}$ meters per day.

\[
\text{Darcy’s Law} \\
q = -K \frac{\Delta h}{\Delta l} \\
= (1.0 \times 10^{-6} \text{ m/s}) \times 0.02 \\
q = 2.0 \times 10^{-8} \text{ m/s day}
\]

\[
\text{Velocity} \\
V = \frac{q}{\Phi} \\
V = \frac{(2.0 \times 10^{-8} \text{ m/s})}{(0.25)} \\
V = 8.0 \times 10^{-8} \text{ m/s} \\
7 \times 10^{-3} \text{ meters per day}
\]
3.2 All metals

Table 3A displays all measured metals—that prior research has identified as elevated in and around cemeteries—for each sampling date and site. The columns of each metal are shaded by a quartile concentration rank. For example, lithium concentrations for each sample collection site and date are color-coded by quartiles to indicate the ranking of lithium concentrations. The shaded quartiles allow for intuitive observations of Table 3A, such as lithium concentrations being generally highest in PMC-2 and lowest in PMC-1 (of the wells).

PMC-1 had the lowest average concentrations of lithium, magnesium, uranium, manganese, arsenic, sodium, and boron compared to PMC-2 and C-1. PMC-2 had the highest average concentrations of lithium, magnesium, uranium, lead, manganese, zinc, barium, and calcium compared to PMC-1 and C-1. The cemetery had the highest average concentrations of chromium, boron, sodium, and cobalt.

### 3.2.1 Trace Metals

<p>| Table 3B: Concentrations of target trace metals |</p>
<table>
<thead>
<tr>
<th>Date</th>
<th>Lithium</th>
<th>Chromium</th>
<th>Lead</th>
<th>Copper</th>
<th>Nickel</th>
<th>Manganese</th>
<th>Arsenic</th>
<th>Zinc</th>
<th>Barium</th>
<th>Calcium</th>
<th>Sodium</th>
<th>Aluminum</th>
<th>Boron</th>
<th>Cobalt</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/22</td>
<td>3.300</td>
<td>0.030</td>
<td>0.020</td>
<td>0.070</td>
<td>0.800</td>
<td>5.100</td>
<td>114.230</td>
<td>0.280</td>
<td>9.870</td>
<td>24.930</td>
<td>44.29</td>
<td>5.29</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>10/22</td>
<td>3.934</td>
<td>0.024</td>
<td>0.100</td>
<td>0.100</td>
<td>0.700</td>
<td>5.100</td>
<td>114.230</td>
<td>0.280</td>
<td>9.870</td>
<td>24.930</td>
<td>44.29</td>
<td>5.29</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>12/22</td>
<td>4.750</td>
<td>0.012</td>
<td>0.100</td>
<td>0.100</td>
<td>0.700</td>
<td>5.100</td>
<td>114.230</td>
<td>0.280</td>
<td>9.870</td>
<td>24.930</td>
<td>44.29</td>
<td>5.29</td>
<td>0.29</td>
<td></td>
</tr>
</tbody>
</table>

PMC-1 had the lowest average concentrations of lithium, magnesium, uranium, manganese, arsenic, sodium, and boron compared to PMC-2 and C-1. PMC-2 had the highest average concentrations of lithium, magnesium, uranium, lead, manganese, zinc, barium, and calcium compared to PMC-1 and C-1. The cemetery had the highest average concentrations of chromium, boron, sodium, and cobalt.

Table 3A: Concentrations of all target metals

Table 3A displays all measured metals—that prior research has identified as elevated in and around cemeteries—for each sampling date and site. The columns of each metal are shaded by a quartile concentration rank. For example, lithium concentrations for each sample collection site and date are color-coded by quartiles to indicate the ranking of lithium concentrations. The shaded quartiles allow for intuitive observations of Table 3A, such as lithium concentrations being generally highest in PMC-2 and lowest in PMC-1 (of the wells).
Table 3B presents the trace metal concentrations for the surficial aquifer wells located at the cemetery and the PMC, along with the averages for each sampling date to enable comparisons. The ratio of the average values of each trace metal concentration is included in quartiles to exhibit the range of difference in concentrations between C-1 and PMC-1. For instance, the ratio row indicates that lithium concentrations were approximately two times higher in the cemetery's surficial groundwater compared to the PMC's surficial groundwater. Generally, C-1 exhibited higher trace metal concentrations than PMC-1 in the shallow aquifer. The most significant disparities in concentrations between C-1 and PMC-1 were observed in uranium, manganese, and arsenic, with C-1 consistently exhibiting higher concentrations of these elements.

The concentrations of uranium, chromium, lead, manganese, aluminum, and lithium revealed a discernible distinction in water chemistry between the shallow and deeper aquifer. As illustrated in Figure 3C, the concentrations from the shallow wells (PMC-1 and C-1) were more similar than the deep well PMC-2, with substantial differences noted between the shallow and deep aquifers for each of the aforementioned metals.
3.3 Bacteria

Figure 4A presents a comparative analysis of the mean bacterial concentrations observed in the three monitoring wells and the stream. Among the well-monitoring locations, the cemetery well exhibited the highest levels of total coliform bacteria, with a concentration of 579.6 MPN/100 mL. In contrast, PMC-2 displayed the lowest concentration of total coliform bacteria, measuring 81.6 MPN/100 mL. The stream, however, revealed the highest levels of coliform bacteria across all sources, registering a concentration of 2,419.6 MPN/100 mL. Notably, the stream was the sole source that contained *E. coli*, with a concentration of 632.6 MPN/100 mL.

3.4 Drinking Water Health Standards

### 3.4.1 Metals

<table>
<thead>
<tr>
<th>Date</th>
<th>Lithium</th>
<th>Magnesium</th>
<th>Sodium</th>
<th>Potassium</th>
<th>Lead</th>
<th>Copper</th>
<th>Nickel</th>
<th>Manganese</th>
<th>Arsenic</th>
<th>Zinc</th>
<th>Barium</th>
<th>Calcium</th>
<th>Nickel</th>
<th>Cobalt</th>
<th>Iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>USGS 8626</td>
<td>0.000</td>
<td>1.972</td>
<td>1.687</td>
<td>0.000</td>
<td>0.00</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
</tr>
<tr>
<td>EPA MCL</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
</tr>
<tr>
<td>9/1/22</td>
<td>0.000</td>
<td>1.972</td>
<td>1.687</td>
<td>0.000</td>
<td>0.00</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
</tr>
<tr>
<td>C-1</td>
<td>0.000</td>
<td>1.972</td>
<td>1.687</td>
<td>0.000</td>
<td>0.00</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
</tr>
<tr>
<td>Stream</td>
<td>0.000</td>
<td>1.972</td>
<td>1.687</td>
<td>0.000</td>
<td>0.00</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 4D: Drinking Water Health Standards
Table 4D identifies the water samples containing concentrations of metals exceeding non-enforceable drinking water standards. These metals are lithium, lead, manganese, arsenic, and aluminum. Table 4C specifies these exceedances. Lithium concentrations in samples from PMC-2 and C-1 surpassed the US Geological Survey Health-Based Screening Level (USGS HSBL) threshold of 10 μg/L. Furthermore, elevated manganese levels were detected in PMC-1, PMC-2, and C-1, exceeding the North Carolina Groundwater Standard for manganese concentrations (50 μg/L) for most collection periods. The samples from PMC-1, PMC-2, and C-1 also contained arsenic and lead concentrations that surpassed the EPA Maximum Contaminant Level Goal (levels at which no adverse effects are expected) set at 0 μg/L for both elements every time. The EPA’s enforceable limits (Maximum Contaminant Levels) for arsenic and lead are 10 and 15 μg/L, respectively. Among the samples in Table 4C, PMC-2 exhibited the highest lithium, manganese, and lead levels, while C-1 contained the most elevated arsenic concentrations. Conversely, PMC-1 generally exhibited the lowest levels of all metals that exceeded the established health standards. The most significant disparity in metal concentrations between any two wells—as depicted in the ratio row of Table 4C—was observed for arsenic between C-1 and PMC-2, with C-1 having more than twice the concentration as PMC-1.

### 3.4.2 Bacteria

The data presented in Figure 4A indicate that the bacterial concentrations observed in the monitoring wells and the stream significantly surpass the thresholds established by the Total Coliform Rule. According to the Total Coliform Rule, no more than 5% of a water system’s monthly samples should yield positive results for total coliform bacteria (U.S. EPA, 2013).
this instance, the elevated levels of total coliform bacteria, particularly at the cemetery and the stream, reveal an apparent exceedance of this standard.

4. Discussion

4.1 Hydraulic Gradient and Groundwater Flow

Our calculations of the hydraulic gradient indicate that groundwater flows from the cemetery to the PMC. Given that groundwater flow rates are on the order of several millimeters per day, groundwater from the cemetery is expected to reach the surficial well at the PMC in a matter of a few years. However, as noted, this is an estimated value rather than a measured value. In addition, this estimation does not account for the additional time it takes water to infiltrate through the soils to the water table. Based on these calculations, it is reasonable to assume that water flowed from the cemetery to the PMC within the decade after the observed problem that the cemetery was inflicting on the West End’s water system and prior to the arrival of city water in the early 1900s.

4.2 Metals

The confined aquifer (PMC-2) generally has higher concentrations of metals than the wells in the surficial aquifer, possibly due to limited interaction with surface water and longer residence times, allowing for the increased dissolution of minerals and metals into the water. The cemetery (C-1) had higher chromium, boron, and cobalt concentrations than PMC-1 and PMC-2, potentially due to the burial activity in the cemetery. Results from Figure 3C suggest that C-1 and PMC-1 are connected and interact, while the water separated by the confining layer in well PMC-2 has distinct water chemistry. Given the apparent connection between the shallow groundwater in the cemetery and PMC, drainage efforts by the City of Durham in 2014 that addressed the perennial surface water flow would not eliminate the potential contaminant transport from the cemetery to the PMC or the surrounding West End neighborhood.

The variations in metal concentrations among the aquifers and streams may be attributable to various geochemical processes, such as dissolution, precipitation, adsorption, and desorption of metals onto minerals and organic matter. Aquifer materials, including rock types and mineral composition, are crucial in controlling the concentrations of metals in groundwater. The metal concentration variability could also derive from anthropogenic activities, such as metal-containing products in the cemetery or contamination from nearby industrial sources. For instance, the mobilization of metals in the cemetery could be influenced by soil disturbance processes associated with excavations, burials, and the decomposition of organic materials, altering the redox conditions in the soil and affecting the solubility and mobility of metals.

Overall, the observed differences in metal concentrations among the four sources may be attributable to a combination of factors, including geochemical processes, anthropogenic influences, seasonal variations, and water-rock interactions. Without additional sampling and geochemical analysis, we cannot identify the source of our measured concentrations. To better understand the source of these metals and their potential impact on water quality, further studies should be conducted to investigate the hydrogeological and geochemical conditions of the deep and shallow aquifers.
4.3 Bacteria

Concentrations of total coliforms decreased from October to December for all the monitoring wells, indicating seasonal variability of bacteria in this region. The stream had the highest concentrations of total coliforms and was the only source to indicate the presence of \textit{E. coli}. Well C-1 had the highest concentrations of total coliforms of the three monitoring wells. These heightened total coliform concentrations not only emphasize potential health hazards if anyone were to use water from these sources (e.g., accessing the stream water), but also accentuate the importance of vigilant monitoring and further research to ensure public health protection.

Additionally, the detection of \textit{E. coli} in the stream, which serves as an indicator of fecal contamination, raises further concerns about the overall water quality and the possibility of waterborne disease transmission.

While total coliforms alone cannot definitively signify the existence of harmful bacteria, they can provide insight into the presence and concentrations of pathogenic bacteria in the surficial and confined aquifer in this setting. Given that C-1 had more than twice the concentration of total coliform bacteria than PMC-1, and both these wells tapped into the same aquifer, there may be higher levels of other bacteria in the cemetery than at the PMC. More robust methods, such as quantitative polymerase chain reactions (qPCR) or genomic sequencing, should be used in the future to determine the specific microbiological pathogenicity of the groundwater at this site.

4.4 North Carolina Groundwater

\textit{Lithium}. In an inventory study of 305 well records in the Triassic Basin of Lee and Chatman Counties, North Carolina, lithium concentrations ranged from 1.46 to 38.1 \(\mu\text{g/L}\) with a median concentration of 7.07 \(\mu\text{g/L}\) (Chapman et al., 2014). \textit{Lead}. Groundwater quality data from a study of the Piedmont physiographic province of North Carolina examined a network of 79 wells in 8 geozones within the Piedmont region. Of the 13 wells in the Raleigh and Charlotte geozone and the 20 wells in the Carolina slate geozone, which are the two geozones that are most similar to the geology of our site, 0 wells had concentrations of lead that exceed the EPA MLC for lead, which is 0.015 mg/L (Harden et al., 2009). \textit{Manganese}. Looking again at the study by Chapman et al. 2014, manganese concentrations ranged from 0.13 to 997 \(\mu\text{g/L}\), with a median concentration of 3.55 \(\mu\text{g/L}\). 35% of the samples (20 samples total) in this study contained manganese that exceeded North Carolina Groundwater Standard for manganese at 50 \(\mu\text{g/L}\).

\textit{Arsenic}. Chapman et al. 2014 reported arsenic concentrations ranging from 0.14 \(\mu\text{g/L}\) to 4.8 \(\mu\text{g/L}\), with a median concentration of 1.1 \(\mu\text{g/L}\) (Chapman et al., 2014). A study conducted by the U.S. Geological Survey examined groundwater quality data from 1994 – 2008 from 346 wells spanning a variety of hydrogeologic and land use settings from New Jersey to Georgia. This examination determined arsenic concentrations to be typically less than 1 \(\mu\text{g/L}\), with the exception of frequently detected arsenic concentrations exceeding 1 \(\mu\text{g/L}\) in groundwater from sedimentary rocks in the Piedmont and Blue Ridge crystalline aquifers (Chapman et al., 2013). The typical range of arsenic concentrations in Durham groundwater is from 1 \(\mu\text{g/L}\) to 9 \(\mu\text{g/L}\) (Gunkle & Bradley, 2005). \textit{Aluminum}. Chapman et al. 2014 observed aluminum concentrations ranging from 2.2 to 14.8 \(\mu\text{g/L}\), with a median concentration of 2.2 \(\mu\text{g/L}\). Looking again at the Harden et al. 2009 study, 1 of the 4 wells in the Raleigh and Charlotte geozone had a concentration of aluminum that exceeded the EPA MCL for aluminum, and none of the three wells in the Carolina slate geozone had aluminum concentrations that exceeded the MCL for aluminum (Harden et al., 2009). Our metal concentrations measure within the known ranges for
parts of North Carolina with similar geology. *Bacteria.* Total coliform bacteria generally do not naturally occur in aquifers. There are 7 instances, mostly in the southeastern part of North Carolina, where groundwater has been detected with levels of coliforms (Chen, 2011). There have been no studies until ours that have detected total coliform bacteria in Durham groundwater.

4.5 Comparison of Other Cemetery Groundwater

4.5.1 Metals

Studies investigating water quality in and near cemeteries vary too greatly, in terms of the setting and metal constituents targeted, to categorize any hydrogeologic and metal concentrations trends and compare them to our results. Only one relatively recent study in the United States has examined the effects of a cemetery on groundwater metal concentrations. However, the monitoring wells in this study tapped into an aquifer at a depth of 5 feet, and there was no hydrogeological description of the test site (Brennan et al., 2018).

4.5.2 Bacteria

The setting of the PMC and Maplewood Cemetery fulfills most of the conditions among cemetery characteristics worldwide that propagate considerable bacteria groundwater contamination levels. Significant concentrations of total coliforms were found in places with similar environmental conditions to Durham—in a well 800 meters from a cemetery in Portugal, in a stream one hundred meters from a cemetery in Brazil, in wells near cemeteries in South Africa, and downslope from an urban cemetery in Zimbabwe (Brennan et al. 2018; Jonker & Olivier 2012; Żychowski & Bryndal 2015). These studies also confirm our results demonstrating higher levels of total coliforms in shallower, unconfined aquifers.

5. Takeaways

The hydrogeological findings from our study align with Pauli Murray's observation of water flow from the cemetery to the PMC. It appears very likely that groundwater travels from the cemetery to the PMC within a span of years. The water chemistry results, derived from both shallow and deep aquifers, indicate a connection between the shallow water at the cemetery and the shallow groundwater at the PMC. The cemetery exhibits higher concentrations of trace metals and bacteria compared to PMC-1. While the city's drainage system may effectively mitigate property damage caused by surface water, it does not address potential groundwater contamination originating from the cemetery. Based on the North Carolina Groundwater Standards and the EPA's Total Coliform Rule, if the groundwater were an active drinking water source, the party responsible for any contamination would be obligated to rectify the issue. Our study is one of few studies to provide insight into metal and coliform concentrations in Durham groundwater. The limitations of our study prevented us from making a causal determination regarding contamination from the cemetery to surrounding groundwater. Analyzing water samples from uncontaminated reference monitoring wells that tap into the same surficial and confined aquifers and comparing them to water samples from our test site would be instrumental in determining the normalcy or uniqueness of our data. Also, the lack of geological core analysis prevents us from fully understanding the groundwater flow rate and possible contaminant transport dynamics.
at our site. It remains unclear whether the transport of metals and bacteria from the cemetery to the well is being hindered or completely halted due to biogeochemical processes, such as adsorption, as groundwater travels from the cemetery. Regular monitoring of the groundwater and surface water at this site can aid in detecting seasonal or periodic changes in metal or bacteria concentrations, helping to identify any emerging issues pertaining to water quality.

6. Conclusion

The concern of contamination in the West End neighborhood from Maplewood Cemetery emerges from an extensive history of racial injustice in Durham. Racial demographics offer a better explanation for the distribution of exclusionary zoning compared to any other measurable factor, such as median income or homeownership rates (Whitmore, 2018). Murray’s grandfather had an option from the City of Durham to develop the land behind his home (now the PMC) for agriculture and brickmaking. The city rescinded this option a few years later and permitted the development of a whites-only cemetery in the African-American neighborhood known as the West End (Murray, 1978). This cemetery then became the source of many issues, and this study looked into the potential problem it posed on its surrounding groundwater. More specifically, our study investigated the impact of Maplewood Cemetery on the groundwater quality at the Pauli Murray Center for History and Social Justice (PMC). The results of our field surveys and water samples reveal that i) water likely flows from the cemetery to the PMC in a matter of years, ii) lithium, manganese, arsenic, lead, aluminum, and total coliform concentrations in the monitoring wells and the stream exceeded various non-enforceable water quality standards, and iii) the cemetery well generally has higher concentrations of metals and bacteria than the shallow well at the PMC. Further investigation involving a reference site and geochemical tracing is necessary to ascertain whether the detected metals and bacteria naturally occur or result from anthropogenic processes related to human burials. This study contributes to the environmental justice literature by highlighting a disproportionate environmental hazard faced by a community of color.
7. Bibliography


Dame, P. F. (1934, December 6). *Drainage - City Correspondence* [Personal communication].


Pine Environmental. (2019). *Bailer, Disposable, FEP, Unweighted - 1.6’’ x 12’’ [Industrial Commerce]*. Bailer, Disposable, FEP, Unweighted - 1.6” x 12”. https://www.pine-environmental.com/products/bailers_disposable_teflon_unweighted_-_1-6_x_12


