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The Impact of Deicing Materials on the Middle and Lower Passaic River Basins, New Jersey : A Geostatistical and Hydrochemical Analysis

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Abstract

Regression analyses of major ion concentration, and specific conductance were compared on a decadal basis from field data of the 1960s, 1980s, 1990s, 2000s, and 2010s to find if there is a statistically significant increase in calcium, chloride, and sodium compared to other major groundwater ions in the Middle and Lower Passaic River Basins. Time series graphical analyses, bivariate coefficient relationships, statistical prediction interval evaluations, and multivariate analyses were used to determine the significance of the individual ion concentration trends. Through ArcGIS, bedrock geochemistry was examined in correlation with well locations, ion concentrations, and road placements. GIS was used to create groundwater flow maps using previously collected hydraulic head measurements.

Time series analyses for the Middle Passaic River Basin indicated that sodium and chloride levels are increasing at different rates throughout the study period. Bivariate plots showed no significant correlation between chloride and sodium nor between chloride and total dissolved solids. Piper diagrams indicate that the groundwater species in this region showed little to no change throughout time. These observations indicate that sodium and chloride show only slight to moderate increases from the 1960s to 2010s in the Middle Passaic River Basin groundwater. The combination of low deicing application, low-porosity basalt, gneiss, and granite bedrock, and the presence of large water reservoirs were considered the responsible variables for the low levels of observable contamination in the Middle Passaic River Basin.

Comparatively, ion concentrations for sodium, chloride, as well as calcium (a component of the less common deicing material liquid calcium chloride) increased at substantially greater rates in the Lower Passaic River Basin. Overall, calcium, sodium, chloride, and total dissolved solids increased at significant rates. Sodium against chloride and calcium against chloride bivariate analyses showed strong correlations. This suggests that there is an observable relationship between the ions individually produced via NaCl and $CaCl_2$. Additionally, calcium and sodium show no correlation with one another, suggesting no intermolecular relationship between the two deicing agents. Through multivariate analyses, a shift in groundwater ionic composition from freshwater to salt water was observed in the Lower Passaic River Basin within the study timeframe. These observations indicate that deicing application in the Lower Passaic River Basin has contaminated the underlying groundwater. The high urbanization, road density, and porous bedrock are considered the responsible variables for this outcome.

MONTCLAIR STATE UNIVERSITY

The Impact of Deicing Materials on the Middle and Lower Passaic River Basins, New Jersey: A Geostatistical and Hydrochemical Analysis

by

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THE IMPACT OF DEICING MATERIALS ON THE MIDDLE AND LOWER PASSAIC RIVER BASINS, NEW JERSEY: A GEOSTATISTICAL AND HYDROCHEMICAL ANALYSIS

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1. Introduction

1.1 Background

The urbanization of the Passaic River Basin in Northern New Jersey has been accompanied by an increasing rate of the application of road deicing materials, potentially influencing groundwater composition. The national annual weighted average of road salt (NaCl) application has increased by approximately 67 percent from 32,030,000 metric tons in the 1960s to 53,490,000 metric tons in the 2000s (Kelly & Matos, 2014). In the State of New Jersey, an estimated 9.6 tons of NaCl are applied annually for each lane-mile of road (NJDOT, 2018). In the winter season of 2017-2018, the New Jersey Department of Transportation (NJDOT) applied 374,921 tons of salt (NaCl) on New Jersey roads (NJDOT, 2018). That same season, to supplement the effects of road salt, the NJDOT utilized an additional 1,187,363 gallons of brine and 830,390 gallons of liquid calcium chloride on NJ roads (NJDOT, 2018). It is therefore imperative to assess how the introduction of road salts has been impacting regional groundwater composition. In the past, various methodologies have been applied to evaluate the effects of road salts in aquifers.

Peters and Turks (1981) utilized linear regression analysis of major ion concentrations versus specific conductance in the Mohawk River, New York to determine the effects of sodium and chloride in the region's groundwater. The study found that between the two study periods, 1951-53 and 1970-74, all the major ions, except sodium and chloride, showed insignificant increases. Sodium and chloride demonstrated a 20 percent increase in yield during the two decades. Through molar ratio and atomic weight analysis of the region's bedrock, the study found that the metasedimentary foundation contributed less than 6 percent of the basin's net dissolved yield of any particular ion.

A later paper by Godwin et al., (2003) also analyzed long-term trends of NaCl in the Mohawk River. The study employed a Schoeller plot to visualize major ion concentration increases from the 1950s to the 1990s. It was found that Na and Cl ion concentrations had increased by 130 and 243 percent within that timeframe, while other ion concentrations remained relatively steady (Godwin et al., 2003).

A separate study by Foos in 2003 on the spatial distribution of road salt contamination in the Cuyahoga Falls, Ohio used multivariate analysis to assess the area's groundwater. The study found that most of the samples were alkali-chloride-rich on piper diagrams and the total dissolved solids (TDS) concentrations ranged from 250 to 4733 mg/L (Foos, 2003). Through the strong correlations found by bivariate analysis between Na and Cl as well as Cl and TDS, the study determined that halite was the major dissolved solid in the target region's water (Foos, 2003).

1.2 Problem Statement

Sodium, chloride, brine, and liquid calcium chloride are deicing agents that have been applied primarily for snow and ice removal from roadways in New Jersey since the early 1960s (NJDOT, 2018). It has been reported from studies of vehicle accident rates in four states in the United States that deicing salts reduced accident rates on highways by 88 percent (Kuemmel & Hanbali, 1992). Though beneficial, the use of road salts has been shown to affect surface water and groundwater quality, and also has been correlated with loss of plant and macro-invertebrate life, loss of biodiversity, nutrient depletion of soils, release of toxins, infrastructure damage, and aquifer stratification and stagnation (Howard, 1993).

Chloride contamination in the groundwater could be a costly and dangerous problem which can result in lead (Pb) and copper (Cu) corrosion of public utilities (Stets et al., 2018).

Understanding the chloride concentrations in the Middle and Lower Passaic River Basins is essential for effective damage control and the prevention of potential lead and copper poisoning risks. The Larson Ratio (LR): (2 [SO_4^{2-}] + [Cl^-]) / [HCO_3^-] is an ionic ratio commonly used to express the potential corrosivity of water (Stets et al., 2018). Ratios under 0.5 would indicate low to slight probability of corrosion, between 0.5 and 1 indicates moderate corrosion probability, and results >1 indicate a clear risk of corrosion (Stets et al., 2018). An inventory analysis from the United States Geological Survey (USGS, 2018) shows that from the 1960s to the 2010s, LR averages in the MPRB show no obvious trend while the LR averages for the LPRB demonstrate an increasing trend that corresponds with Cl^- concentrations (Table 1). In the 1990s, the MPRB LR average spikes, however this is linked to the drastic increase in SO_4^{2-} concentration within that same decade and is therefore not related to Cl^- trends. On the other hand, the LPRB shows an increasing LR average that is directly related to the increasing Cl^- concentrations. The increasing corrosive potential of the groundwater in the LPRB is of concern, and herein shall be compared with the MPRB to determine a potential cause.

Table 1. Cl-, SO_4^{2-}, and HCO_3^- ionic concentration averages and the corresponding Larson Ratio average of the Middle and Lower Passaic River Basin groundwater from the 1960s to the 2010s (USGS, 2018).

Middle Passaic River Basin					Lower Passaic River Basin				
Decade	Cl (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	Larson Ratio Average	Decade	Cl (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	Larson Ratio Average
1960s	8.81	22.88	91.82	0.59	1960s	29.38	55.17	172.63	0.81
1980s	25.27	26.02	105.19	0.73	1980s	42.65	38.51	154.29	0.78
1990s	39.00	117.49	35.71	3.68	1990s	160.55	115.62	-	-
2000s	71.32	13.49	15.99	0.39	2000s	304.20	33.98	239.25	1.56
2010s	-	-	-	-	2010s	443.93	41.72	217.44	2.43

1.3 Study Objectives

This project utilizes statistical analyses aimed at evaluating deicer road salts as the source of groundwater contamination, using the historical water quality inventory collected from the 1960s to the 2010s by the USGS. Middle and Lower Passaic River Basin groundwater samples were analyzed independently for their significant variations in road density, geology, and hydrology. The separate study of each basin allowed for insight into the compounding effects these variables have on road salt contamination in groundwater. The objective of this study is to determine if road deicing materials are contaminating the groundwater of these two contrasting areas at different rates. Also, to determine if groundwater movement has aided in the distribution of chemical ions in the area over the years. The specific aims are:

- investigating trends of major groundwater ions (Ca, Mg, Cl, and Na) in groundwater;
- determining relationships between ions through bivariate analysis;
- evaluating fluctuations of the groundwater hydrochemical composition;
- determining a relationship between groundwater flow and chemical ion distribution pattern, through potentiometric and ion concentration contouring;
- examining possible effects of road deicing salts on groundwater.

1.4 Study Area

1.4.1 Location and Setting

The Middle Passaic River Basin and Lower Passaic River Basin are situated on the northern section of the Atlantic Seaboard Fall Line, a 900-mile escarpment on the eastern coast of the United States, where the Piedmont Plateau and Atlantic Coastal Plain meet (Naeser et al., 2016). This fall line marks the boundary between the hard, metamorphosed, and elevated terrain of the plateau and the sandy, sedimentary, and flat coastal plain (Naeser et al., 2016). The MPRB and LPRB are identified by the New Jersey Department of Environmental Protection respectively as Watershed Management Area 03 and Watershed Management Area 04 (Figure 1).

The MPRB lies on the Piedmont Plateau, to the west of the ridge. The MPRB consists of mostly suburban townships, lying in Passaic County and including smaller sections of Bergen, Morris, and Sussex counties (NJDEP-Watershed Restoration-Watershed Information, 2018). The MPRB is overlain by 1,305 miles of road (Figure 2) (NJ Bureau of GIS, 2018). This equates to a total of 12,580.4 tons of road salt being used in the MPRB for the year 2017.

The Lower Passaic River Basin lies on the Atlantic Coastal Plain, to the east of the Atlantic Seaboard Fall Line. The Atlantic Coastal Plain is an area of low relief extending 2,200-miles from New York to Florida (Anderson, 1986). The coastal plain's average elevation is less than 900 meters above sea level and is mostly comprised of sedimentary bedrock (Anderson, 1986).

The LPRB consists of major urbanized and industrial cities such as Newark, Paterson, Clifton, and East Orange ("NJDEP-Watershed Restoration-Watershed Information", 2018). The LPRB is densely crowded by 3,273.1 miles of road (Figure 3) (NJ Bureau of GIS, 2018). The density of roads in the LPRB (17.4 lane-miles per sq. mi) is over 300 percent greater than the road density of the MPRB (5.5 lane-miles per sq. mi). This equates to 31,550 tons of road salt being used in the LPRB in the year 2017 (Table 2).

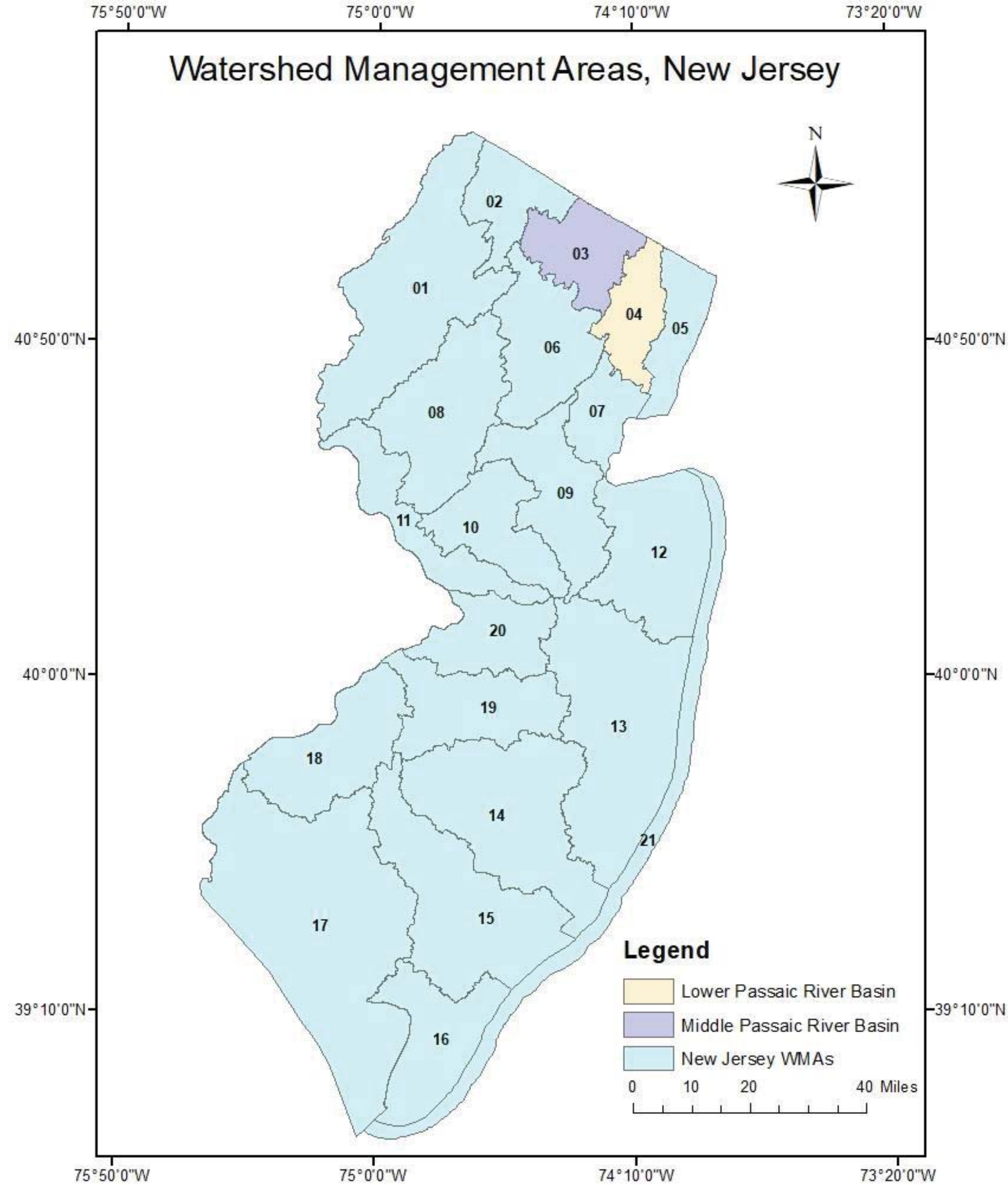


Figure 1. Lower and Middle Passaic River Basins represented as Watershed Management Areas 03 and 04 (NJDEP, 2009).

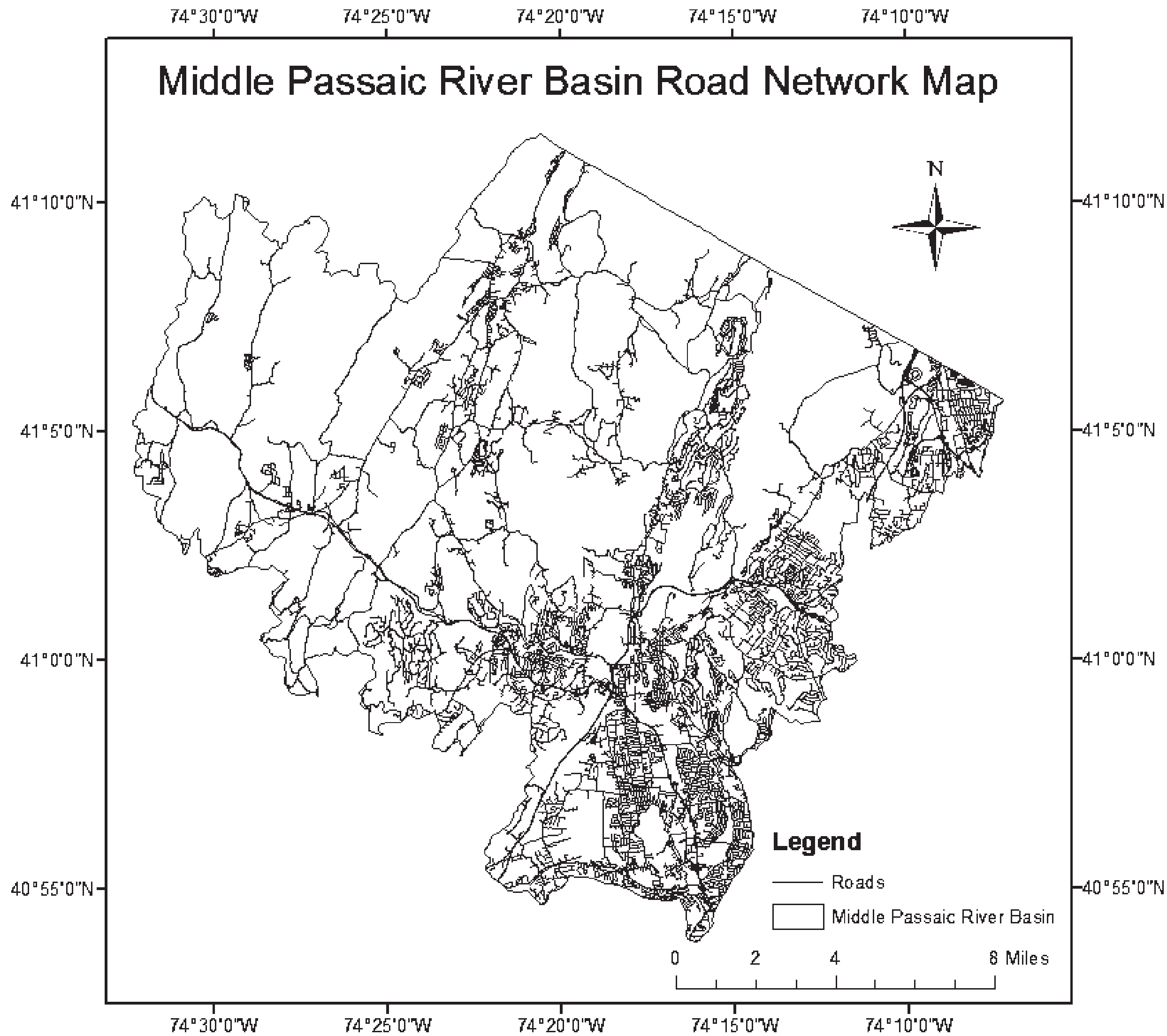


Figure 2. Spatial distribution of roads in the Middle Passaic River Basin, New Jersey (NJ Bureau of GIS, 2017).

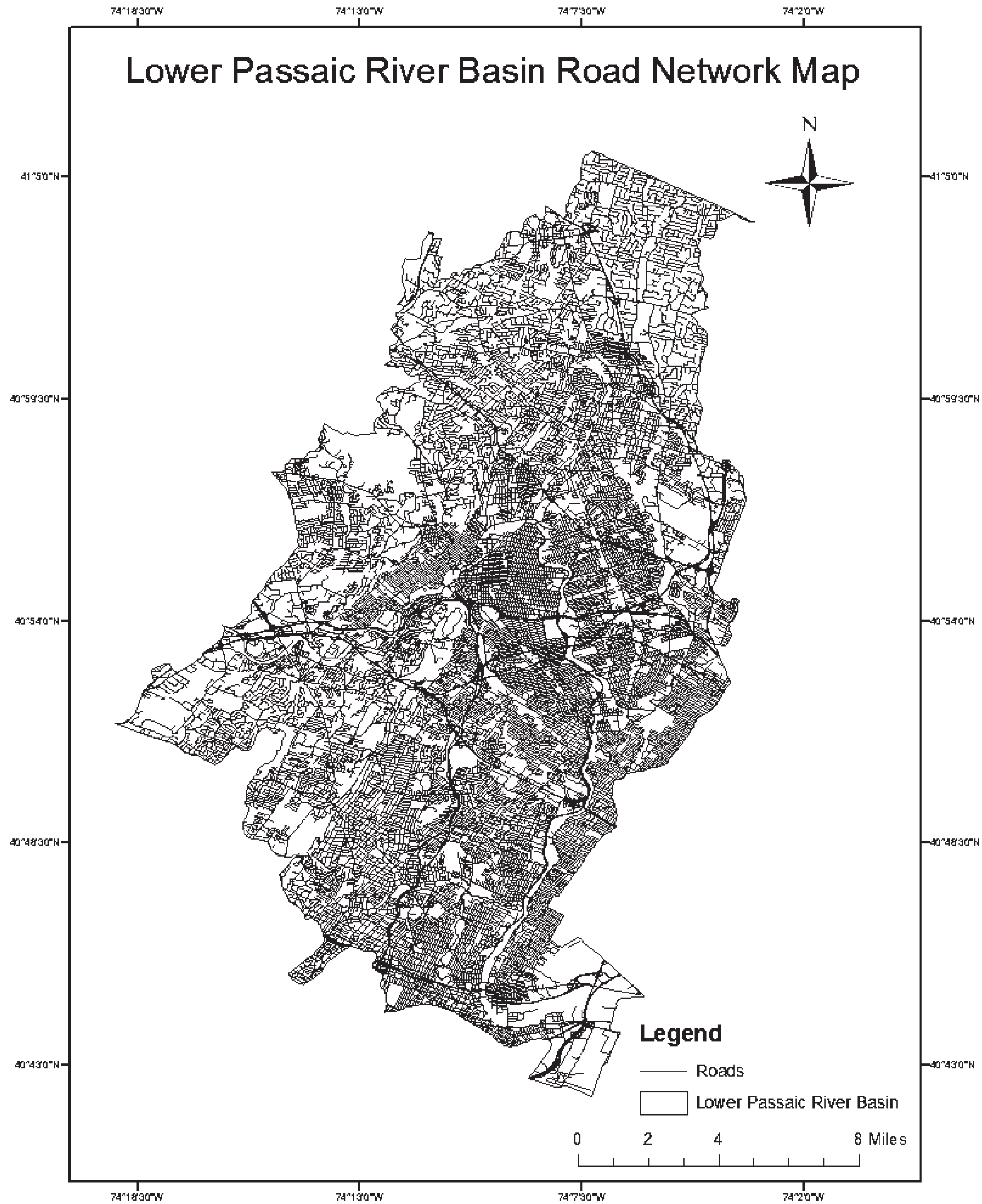


Figure 3. Spatial distribution of roads in the Lower Passaic River Basin, New Jersey (NJ Bureau of GIS, 2017).

Table 2. De-icing statistics for Lower and Middle Passaic River Basins for the year ending in 2017 (Calculated from NJDOT and USGS data).

Location	Total road miles (mi)	Total NaCl (tons)	Total Brine (gal)	Total Liquid $CaCl_2$ (gal)
Lower Passaic River Basin	3,273.14	31,550.00	99,917.87	69,878.21
Middle Passaic River Basin	1,305.15	12,580.41	39,841.77	27,863.60

De-icing statistics for the entirety of New Jersey for the year ending in 2017 (Calculated from NJDOT and USGS data).

NJ Total Miles (mi)	38,896.00
NJ Total NaCl Application (tons)	374,921.00
Brine (gal)	1,187,363.00
Liquid $CaCl_2$ (gal)	830,390.00
NJ NaCl (tons/lane-mile)	9.64
NJ Brine (gal/lane-mile)	30.53
NJ $CaCl_2$ (gal/lane-mile)	21.35

1.4.2 Hydrology

The MPRB is made up of four watersheds: Pompton, Ramapo, Pequannock, and Wanaque River Watersheds, together comprising a total of 237.9 sq. mi (Figure 4). The Ramapo, Pequannock, and Wanaque rivers all flow into the Pompton River, making it a major tributary to the Upper Passaic River. The MPRB contains major water supply reservoir systems such as the Wanaque Reservoir, the largest surface water reservoir in New Jersey (NJDEP-Watershed Restoration-Watershed Information, 2018).

An in-depth analysis of the Ramapo watershed of the Middle Passaic River Basin hydrology by John Vecchioli and E.G. Miller states that supplies of over 1,000 gallons per minute are available from wells tapping the stratified drift in the Ramapo valley, providing 75 percent of the total groundwater pumped for public use in the basin (Vecchioli & Miller, 1974). The groundwater and surface water of the basin were considered as a single resource after a comparison of chemical analysis of water from the Ramapo River with water from wells tapping the valley-fill deposits showed that the two waters are similar (Vecchioli & Miller, 1974). This link between surface water and groundwater is because the Ramapo River flows over a thin, 100ft layer of glacial drift underlain by low-porosity Precambrian gneiss bedrock (Vecchioli & Miller, 1974). The impermeable bedrock of the region acts as a barrier, preventing the surface water from seeping deeper into the ground, diffusing, and being stored. The study also found that groundwater and surface water quality vary at times of low-flow according to the category of rock from which the water originates. It also noted that groundwater from the MPRB was found to be low in total dissolved solids (TDS); less than 127 mg/L (Vecchioli & Miller, 1974).

The LPRB consists of two watersheds: Lower Passaic River Watershed and Saddle River Watershed, together comprising a total area of 188.5 sq. mi (Figure 5). The Lower Passaic River watershed is a result of the Pompton River's downstream convergence into the Newark Bay. The major tributaries for the Lower Passaic River are the Saddle River, Preakness Brook, Second River, and Third River (NJDEP-Watershed Restoration-Watershed Information, 2018). Urban development dominates the landscape for both watersheds within the LPRB. The Brunswick Formation can be depended upon to yield 100-200 gallons per minute to wells, nearly one-tenth of the yield of the MPRB (Vecchioli & Miller, 1974). Additionally, in 1974, water from the LPRB groundwater was mineralized with a TDS content as much as 278 mg/L, over twice the concentration found in the MPRB (Vecchioli & Miller, 1974).

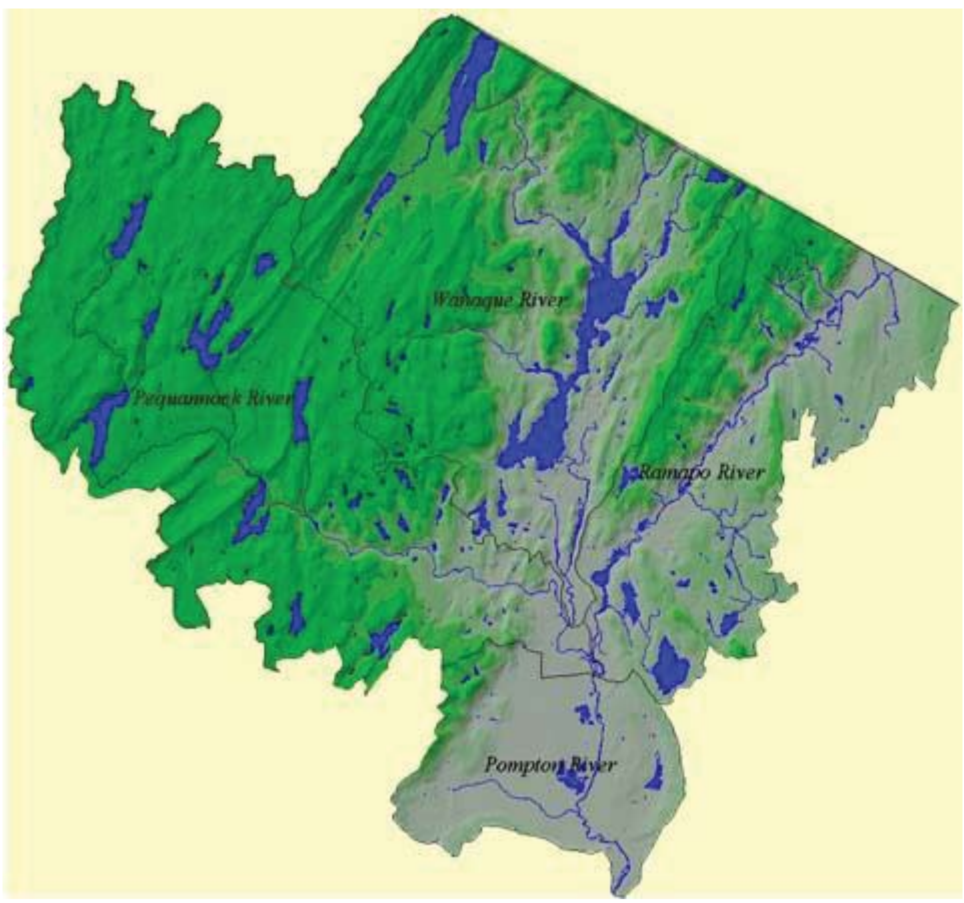


Figure 4. Illustration of the Middle Passaic River Basin watershed depicting the major rivers which drain an area of 237.9 sq. mi. (Reprinted from New Jersey Department of Environmental Protection, 2012).

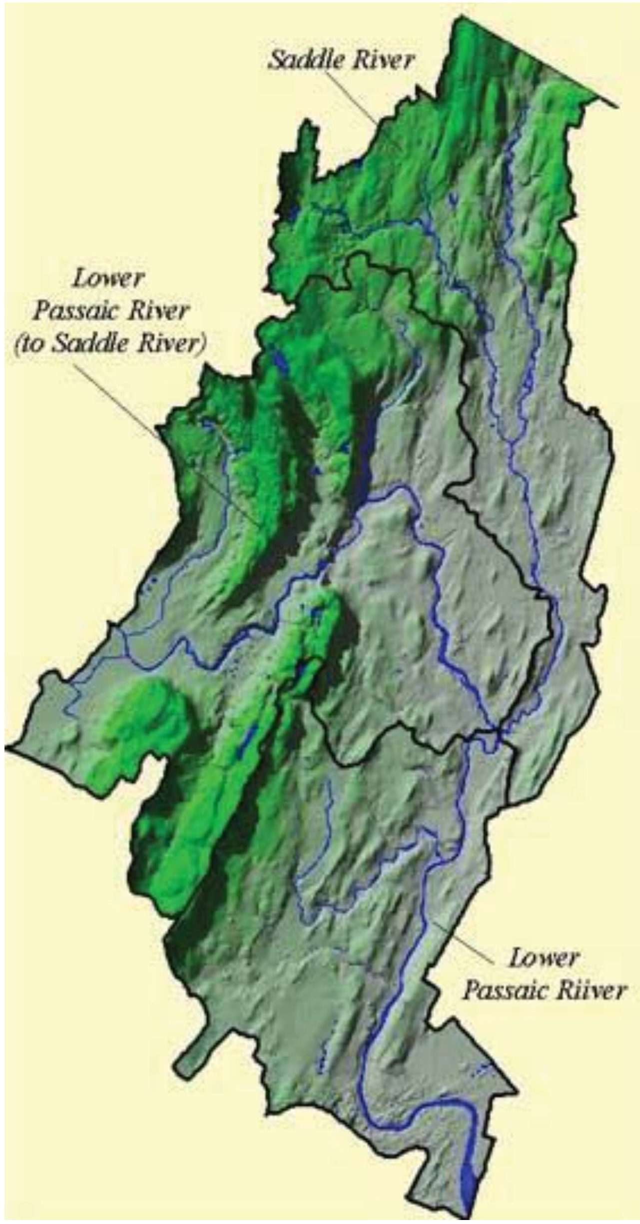


Figure 5. Illustration of the Lower Passaic River Basin watershed depicting the major rivers which drain an area of 188.5 sq. mi. (Reprinted from New Jersey Department of Environmental Protection, 2012).

1.4.3 Geology

The MPRB geologic formation was created through numerous mountain-building events such as the Greenville and Taconic orogenies (Naeser et al., 2016). The bedrock consists of mostly igneous and metamorphic rock such as basalt, gneiss, and granite (Figure 6). These rock types are not adequate sources of Ca^{2+}, Mg^{2+}, Na^{+}, Cl-, or SO_4^{2-} (Ries, 1901). There are also small portions of sandstone found in the MPRB. Sandstone is a sedimentary rock with high erosion rates and is considered a potential source for Ca^{2+} and Mg^{2+} due to its binding elements consisting of calcites and shales (NJDEP, 2018). The influence of denudation on Ca^{2+} and Mg^{2+} ion yield is likely insignificant because the total surface area of the sedimentary contributors is less than 10 percent of the total basin area.

The LPRB bedrock largely originates from the Brunswick Formation of Triassic age (Olsen, 1980). It consists of a heterogeneous mix of basalt, shale, sandstone, and conglomerate, which are known potential sources for Ca^{2+} and Mg^{2+} (Figure 7). To a much lesser extent, some basalt regions can be found in the area. The geology of the LPRB therefore suggests a significant natural source of Ca^{2+} and Mg^{2+}. Additionally, the LPRB's high storage capacity and heterogeneity permits the natural evolution of major groundwater ions Ca^{2+}, Mg^{2+}, Na^{+}, Cl-, HCO_3^{-}, and SO_4^{2-} as shown in Figure 8 (Alley, 1993).

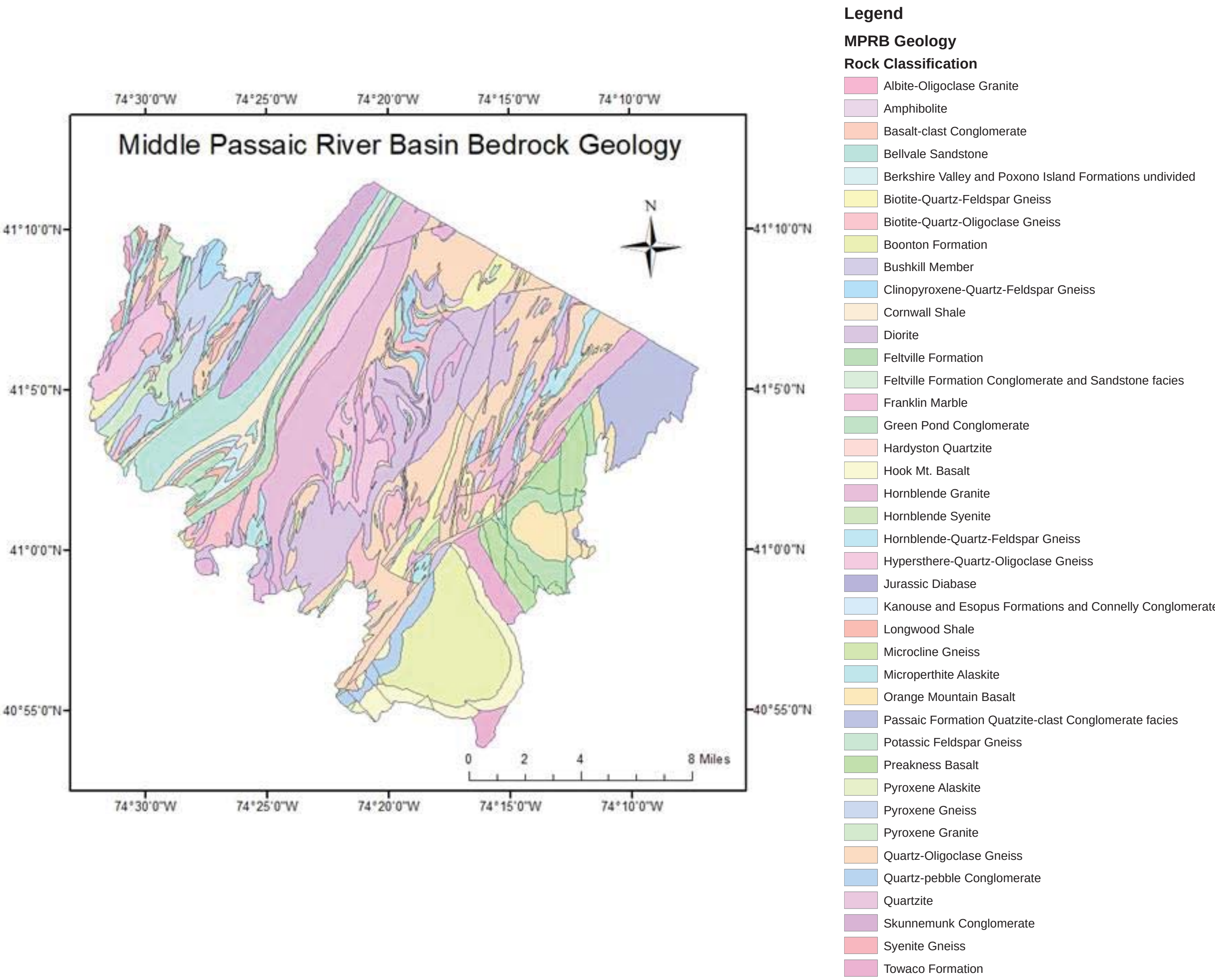


Figure 6. Bedrock geology for the Middle Passaic River Basin, New Jersey (NJDEP, 2007).

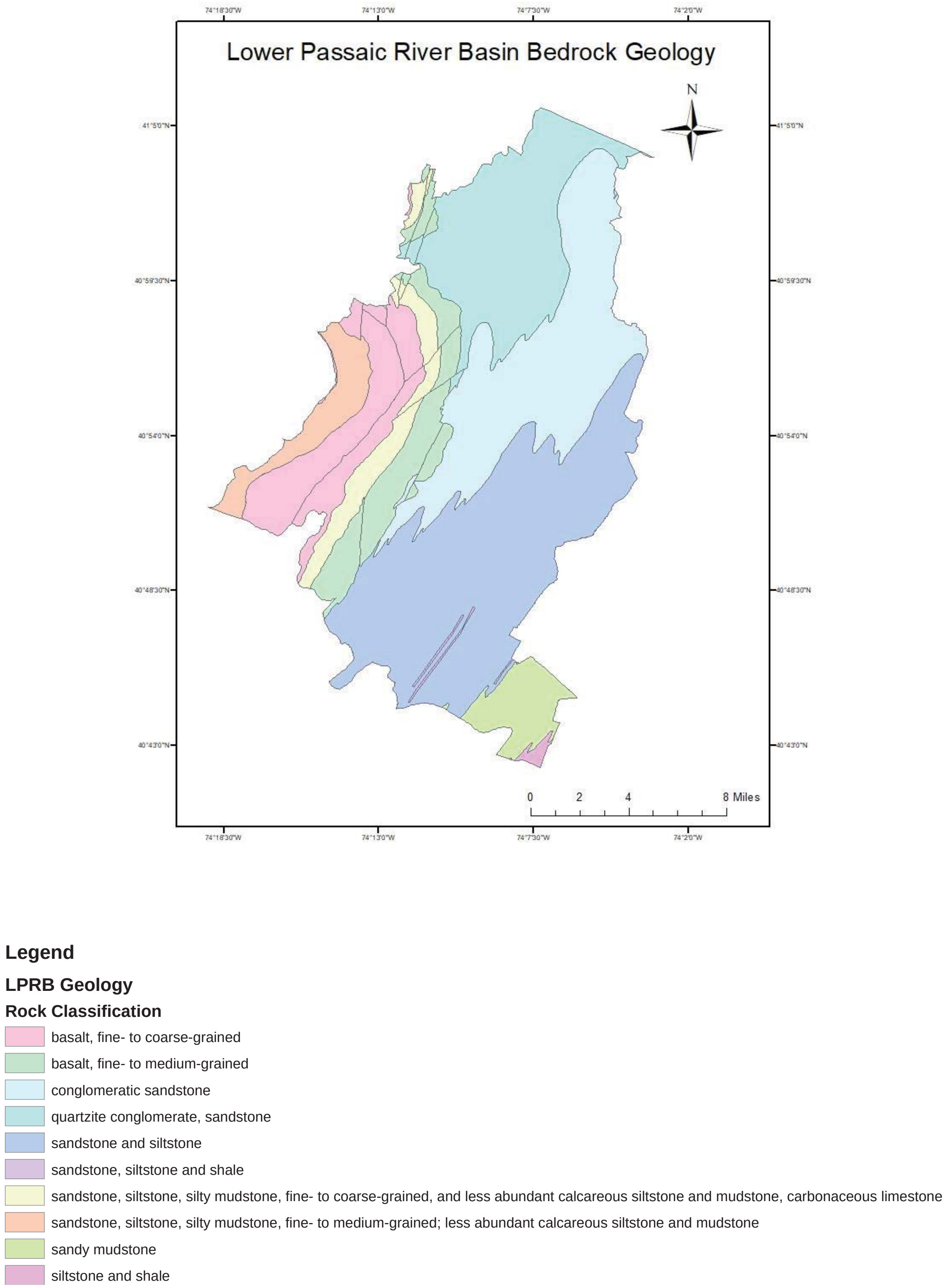


Figure 7. Bedrock geology for the Lower Passaic River Basin, New Jersey (NJDEP, 2007).

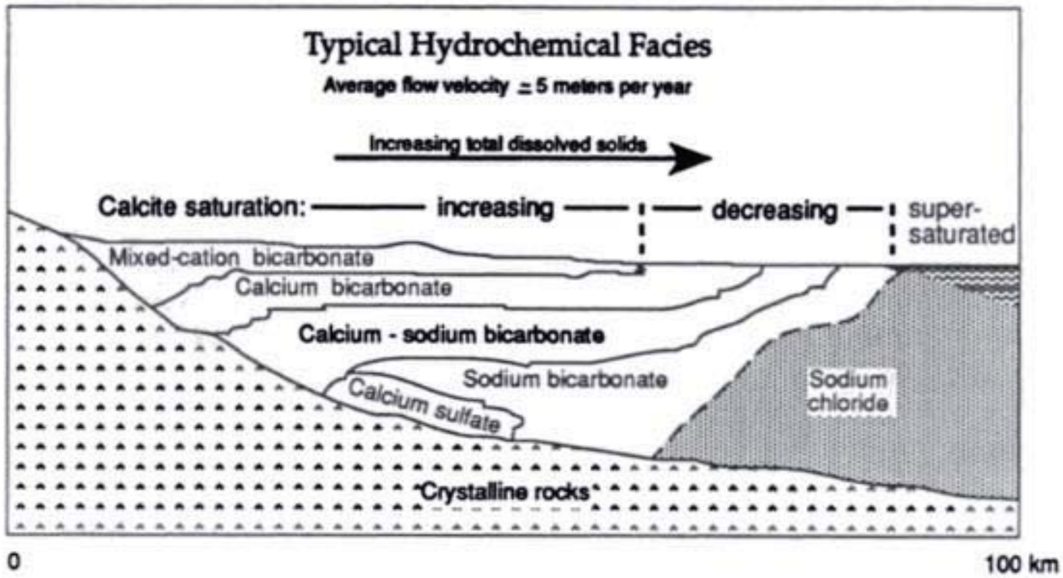


Figure 8. A representation of geochemical reactions in a heterogenic aquifer (Reprinted from Alley, 1993).

1.5 Natural Groundwater Evolution

According to the Chebotarev Sequence, Ca^{2+} and Mg^{+} deposits occur naturally through bedrock erosion in young and active groundwater stages, commonly found in upper (shallow) zones (Chebotarev, 1955). HCO_3^- and SO_4^{2-} are abundant in the intermediate zone, where water is less active. Cl^- anions are naturally allocated in aged and stagnant groundwater, termed as the lower (deep) zone. It is important to note the natural occurrence of Cl^- in groundwater takes hundreds of thousands to millions of years (Freeze & Cherry, 1979).

TDS measurements assist in recognizing ion sources and the natural hydrochemical makeup of groundwater. A TDS concentration under 1,000 mg/L is indicative of freshwater. Freshwater bodies should have ion compositions largely consistent of Ca^{2+} and HCO_3^- (Fetter, 2014). On the other hand, a TDS concentration of 10,000-100,000 mg/L is indicative of saline water. Aged and stagnant groundwater bodies tend to become saline and should contain higher levels of Na^{+} and Cl^{-} (Freeze & Cherry, 1979).

Considering it takes thousands to millions of years for saline bodies to naturally occur, a sudden increase in Na^{+}, Cl^{-}, and TDS between the 1960s and 2010s would suggest the anthropogenic application of deicing materials is indeed contaminating regional groundwater (Fetter, 2014). Significant Ca^{2+} concentration increases within the study timeframe may also be indicative of $CaCl_2$ liquid application. In contrast, a uniform increase in all major ions would suggest a domestic source such as bedrock weathering.

2. Methodology

2.1 Data Collection

The field parameters were collected from the U.S Geological Survey, which stores accumulated sample data from wells nationwide. One hundred and thirty-eight MPRB samples and 83 LPRB samples were collected from the USGS database and analyzed in decadal portions from the 1960s, 1980s, 1990s, 2000s, and 2010s for analysis of ion percent and mean fluctuations. A lack of data representative of the 1970s in both areas led to the omission of analysis for that decade. The data were collected from various agencies such as the USGS National Water-Quality Assessment (NAWQA), U.S Environmental Protection Agency (USEPA), and the NJ Department of Environmental Protection (NJDEP) amongst numerous others for individual research programs throughout the study timeframe (the data are stored in the USGS online catalogue and can be retrieved by accessing https://nwis.waterdata.usgs.gov/nwis/gwlevels?).

Field parameters used for this research consisted of specific conductance (uS/cm), TDS (mg/L), and ion mass concentration (mg/L) for major ions Ca^{2+}, Mg^{+}, K^{+}, Na^{+}, Cl^{-}, HCO_3^{-}, SO_4^{2-},

CO_3^{2-}, and F^-. The data were imported to Excel version 14.4 for statistical analyses, and then into ArcGIS to create potentiometric maps and ion concentrations contouring. The shapefiles for the watershed basemaps (including boundaries, elevation, bedrock, and roads) were downloaded from the NJDEP Bureau of GIS (NJ Bureau of GIS, 2018).

2.2 Data Analyses

2.2.1 Time Series and Schoeller Graphical Analysis

The mean values of the parameters Ca^{2+}, Mg^{2+}, Na^+, Cl^-, and TDS were plotted against time, in decades, for organized visualization of concentration trends. Additionally, Schoeller plots, which utilize a logarithmic y-axis, were created to display magnitudes of ion concentrations on a decadal basis. Time plots offer insight into ionic concentration trends throughout time and offer some general understanding to ion-ion relationships as well as their sources of origin.

2.2.2 Prediction intervals

To examine the influence of deicing materials on groundwater, individual regression analysis of each major ion, Ca^{2+}, Mg^+, Na^+, and Cl^- was conducted as a function of the independent variable, specific conductance (Peters & Turk, 1981). The linear trends between individual ions and specific conductance were compared between two sets of time: 1960s and 1990s for MPRB, 1960s and 2000s for LPRB. These sample dates were chosen for comparison as they provided a sufficient data count for regression analysis and are representative of both incipient and recent stages of road salt application. Ninety-five percent prediction intervals were assigned to the 1960s dataset to determine whether the actual future observations fell within statistical estimates. The prediction interval for the dependent variable (y) was calculated from the independent variable (x), using the equation (Dixon and Massey, 1969; Snedecor, 1946):

$$\hat{y}_h \pm t_{(\alpha/2,n-2)} \times \sqrt{MSE\left(1+\frac{1}{n}+\frac{(x_h-\bar{x})^2}{\sum(x_i-\bar{x})^2}\right)} \quad \text{...(1)}$$

where:

y_h = predicted value of the response

x_h = predictor

$t_{(\alpha/2,n-2)}$ = student-t (statistic for applicable degrees of freedom)

$\sqrt{MSE\left(1+\frac{1}{n}+\frac{(x_h-\bar{x})^2}{\sum(x_i-\bar{x})^2}\right)}$ = standard error of the prediction

2.2.3 Bivariate Analysis

Bivariate regression analysis was used to examine individual ion to ion relationships. Comparison of major ions, Ca^{2+}, Mg^{+}, Na^{+}, and Cl^{-}, as well as TDS allows for insight into the correlations between two variable concentration fluxes. Pearson's correlation coefficient, r, is indicative of the relationship between two data variables. Ions with correlation coefficients near or equal to a value of 1 have a positive, or unison, relationship and possibly originate from an analogous source (Hocking et al., 2018). Conversely, correlation coefficients closer to -1 have a negative relation with one another. Correlation coefficients close to 0 are of no relation with each other and in this study, would be indicative of separate ion origins (Hocking et al., 2018).

The coefficient of determination, r^2, shows the percentage of variation in a bivariate regression analysis. The r^2 is simply the squared value of the correlation coefficient, r, and since squared values are always positive, the r^2 value always ranges from 0 to 1 with values closer to 1 signifying stronger correlation. The coefficient of determination is more useful in identifying bivariate correlations in regression analyses (Boyte et al., 2017).

Sample size, n, must be taken into consideration during Pearson correlation analysis, since analysis of a sample size ≤ 2 will always have a meaningless r and r^2 value of 1 ("Degrees of Freedom", 1998). For bivariate analysis; df = n - 2, where df = degrees of freedom and n = sample size. Additionally, to be considered statistically significant, an r value should exceed a critical value which is inversely related to the degrees of freedom ("Degrees of Freedom", 1998). As such, critical value decreases as the sample size increases. Therefore, the statistical significance of a bivariate analysis via Pearson's correlation coefficients increases along with sample size.

2.2.4 Groundwater Species

Piper diagrams allowed for multivariate graphical representations of the water composition in the study areas. The piper diagrams were created through an excel program from "USGS Nevada Excel for Hydrology" (2018). For a proper representation of groundwater composition on the diagram, well samples must have provided ion concentration measurements for the following: Ca^{2+}, Mg^{+}, Na^{+}, K^{+}, HCO_3^{-}, SO_4^{2-}, and Cl^{-}. Since a large portion of the dataset did not contain all the necessitated parameters, the sample set for this multivariate analysis was reduced to 41 total samples for MPRB and 33 total samples for LPRB.

In a piper diagram, cations and anions are segregated into individual Gibbs triangles, which are then projected onto a diamond plot in the center. The center diamond therefore provides a multivariate depiction of the sample dataset's ionic composition. Piper diagrams were composited for each decade to distinguish the groundwater ionic composition changes throughout time.

2.2.5 Potentiometric and Ionic Concentration Maps

Ion concentration and hydraulic head potentiometric maps were created for each decade within the study timeframe. The maps depict ion concentration and hydraulic head highs and lows throughout the geography of MPRB and LPRB. The ion concentration maps demonstrate general trends and concentration contours over the landscape for each decade. The hydraulic head potentiometric maps have a backdrop of the geography's elevation and provide significant information on groundwater flow, recharge areas, and discharge areas.

2.2.6 Inconsistencies

The amount of field parameters and/or water quality samples was not consistent for every well site. Well site locations and data counts were not congruent from decade to decade. Some wells had multiple dates in which samples were collected, others only had one. If a single well had multiple sets of data within a single decade, only the most recently dated sample within that decade, for said sample, was used for data analysis. This was done to prevent a single well from having a greater influence than it ought on the data results. On rare occasion, samples contained datasets with extreme measurement deviations of over 1000% comparatively to other wells within the same decadal timeframe and were therefore considered anomalies.

3. Results

3.1 Middle Passaic River Basin Results

3.1.1 MPRB Time Series and Schoeller Graphical Analysis

Figures 9a, 9b, 9c, and 9d depict concentration increases over time for Cl, Ca, Mg, and TDS. There is no significant increasing trend shown for Na (Figure 9e). This indicates that Na and Cl levels are increasing at different rates, indicating a possible lack of relation between these two ions, and presenting no evidence of NaCl contamination. It is also observed that Ca and Mg ions are increasing at different rates, suggesting that there may be an outside source for Ca such as

$CaCl_2$. However, the overall increasing concentration trend observed in most of the major ions demonstrates that there is no noticeable contamination of NaCl and $CaCl_2$ on the MPRB groundwater. Only chloride concentrations demonstrate distinct increases every decade, suggesting there may be a unique source of chloride contamination. The lack of significant NaCl and $CaCl_2$ influence on the groundwater could be due to their relatively low application amounts in the area (52.88 tons/sq. mi). The Schoeller plot indicates a constant increase in all ion concentrations throughout time, except for Na and SO_4^{2-} which decreased in the 2000s (Figure 10). Overall, the time plots indicate that most of the major groundwater ions have undergone concentration increases. However, Na and Cl are increasing at different rates, suggesting they may stem from different sources. The mean, range, and standard deviation of the field parameters for each major ion throughout the sample period are depicted on Table 3.

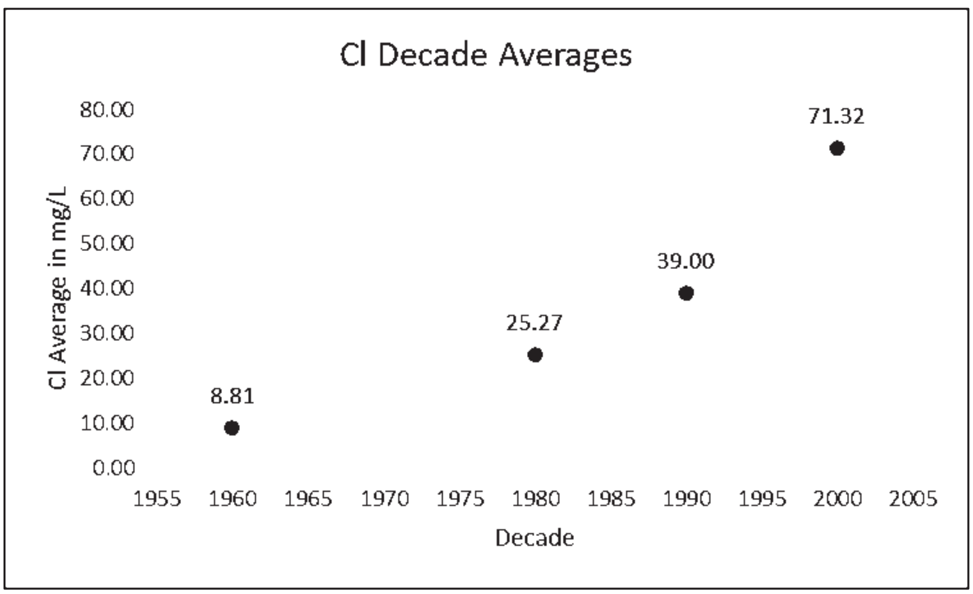


Figure 9a. Cl ion concentration averages for each decade, 1960s-2000s in the Middle Passaic River Basin, New Jersey (1970s data not available).

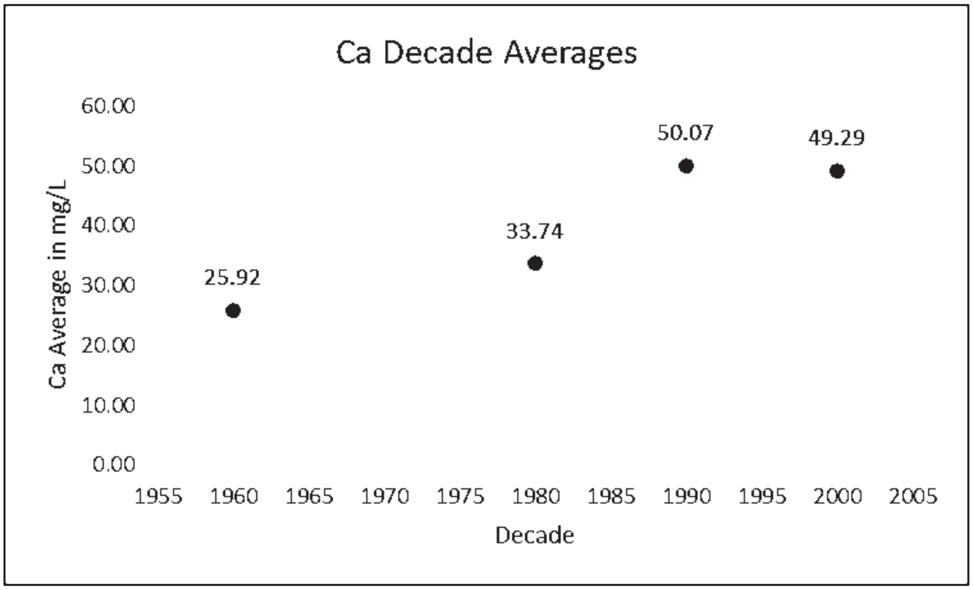


Figure 9b. Ca ion concentration averages for each decade, 1960s-2000s in the Middle Passaic River Basin, New Jersey (1970s data not available).

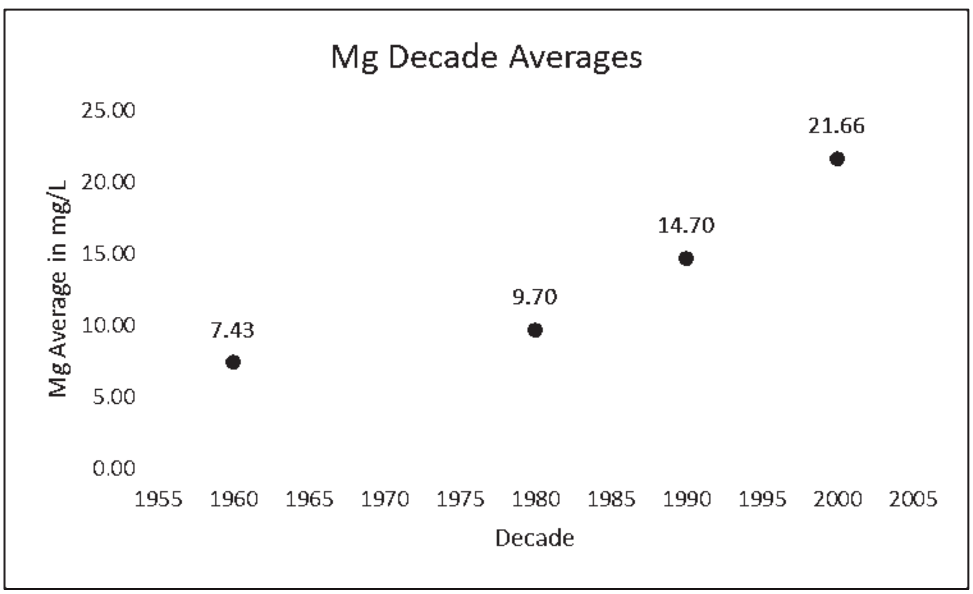


Figure 9c. Mg ion concentration averages for each decade, 1960s-2000s in the Middle Passaic River Basin, New Jersey (1970s data not available).

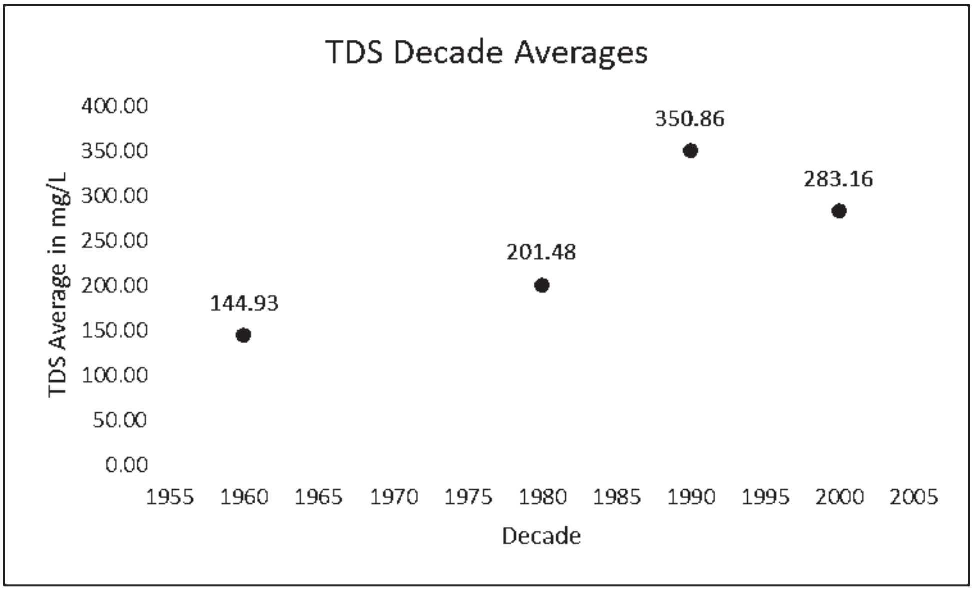


Figure 9d. Total dissolved solid concentration averages for each decade, 1960s-2000s in the Middle Passaic River Basin, New Jersey (1970s data not available).

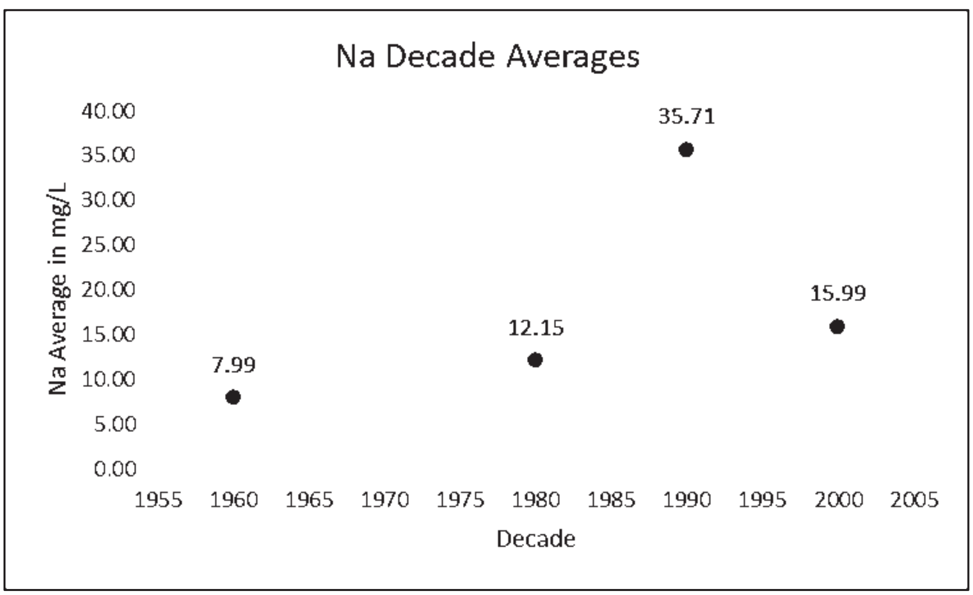


Figure 9e. Na ion concentration averages for each decade, 1960s-2000s in the Middle Passaic River Basin, New Jersey (1970s data not available).

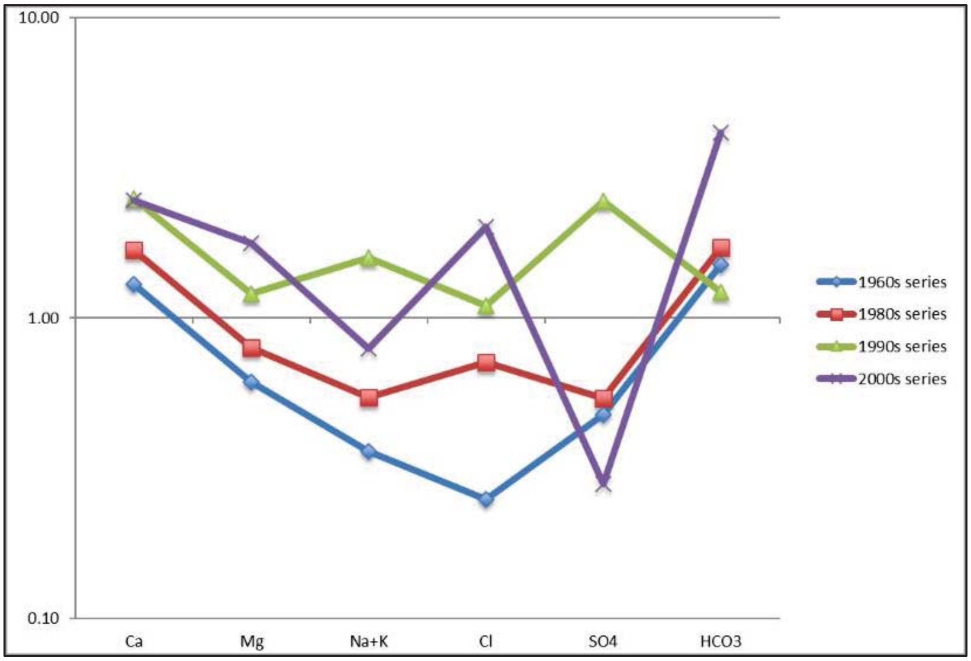


Figure 10. A Schoeller depicting log (concentration) of major ions for the 1960s, 1980s, 1990s, and 2000s in the Middle Passaic River Basin, New Jersey.

Table 3. Mean, standard deviation, range, and data count of major ion concentration and total dissolved solids, Middle Passaic River Basin, New Jersey (concentrations are in mg/L).

Ion	Decade	Mean	SD	Max	Min	Count
Na^{+}	1960s	7.99	3.98	16.00	3.40	17
	1980s	12.15	7.55	40.00	2.20	83
	1990s	35.71	77.38	330.00	5.45	17
	2000s	15.99	16.39	47.50	4.81	7
Mg^{2+}	1960s	7.43	3.47	16.00	2.70	17
	1980s	9.70	5.25	25.00	1.10	86
	1990s	14.70	13.17	49.00	3.60	17
	2000s	21.66	21.61	63.50	3.40	7
Ca^{2+}	1960s	25.92	8.55	44.00	7.60	17
	1980s	33.74	13.93	63.00	5.80	86
	1990s	50.07	40.77	170.00	8.64	17
	2000s	49.29	45.84	137.00	10.10	10
Cl^{-}	1960s	8.81	6.09	25.00	1.90	17
	1980s	25.27	21.29	130.00	1.20	92
	1990s	39.00	30.68	106.00	1.86	17
	2000s	71.32	75.79	179.00	3.40	10
TDS	1960s	144.93	42.79	228.00	58.84	17
	1980s	198.58	76.77	419.22	44.13	86
	1990s	353.02	423.59	1853.38	73.55	17
	2000s	286.83	287.71	801.66	88.26	4

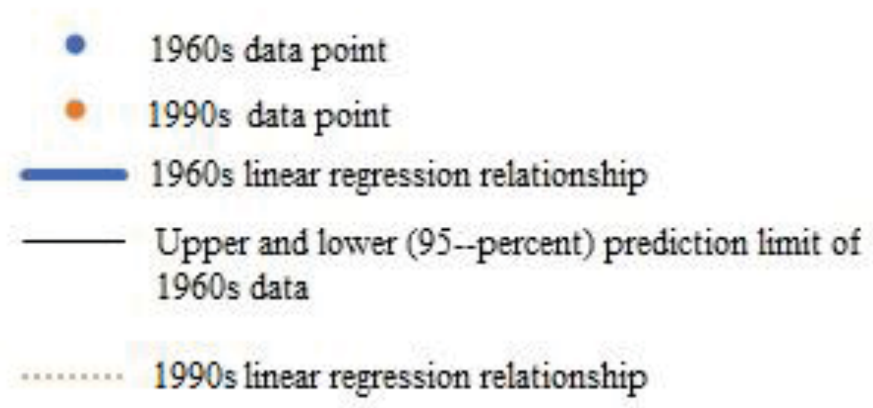
3.1.2 MPRB Prediction Intervals

Overall, every major ion showed an increase in concentration percentage of at least 100% (Table 4). The table shows that Na (360.69%) and Cl (330.76%), uniquely, have drastic increases 3 times larger than the other major ions. Na and Mg linear regression comparisons (Figures 11a and 11b) from the 1960s and 1990s display a concentration ion trend which is lower than predicted by the 95% prediction interval. Ca comparisons are within prediction (Figure 11c). Cl comparisons are significantly above prediction (Figure 11d). The results of the regression analysis in conjunction with prediction intervals showcase that most groundwater ion concentrations of the MPRB have increased, but not at an unexpected rate. The only ion to show concentration increases above predicted rates, Cl, could be assumed to be the result of an additive effect between NaCl and $CaCl_2$ road deicing application. If that assumption were correct, it could be said that there is some measurable evidence of deicing in the MPRB. If not, this may be evidence of a unique outside source for Cl ions.

Table 4. Calculated mean yield of major ion concentrations from Middle Passaic River Basin, New Jersey (all yields are in mg/L).

Constituent	1960s	1990s	Difference	Percent Increase
Sodium (Na)	8.11	37.37	29.26	360.69%
Potassium (K)	0.46	1.27	0.81	176.39%
Magnesium (Mg)	7.44	15.12	7.68	103.31%
Calcium (Ca)	25.54	51.13	25.60	100.23%
Chloride (Cl)	8.89	38.31	29.42	330.76%
Sulfate (SO4)	22.88	49.83	26.95	117.76%

Legend



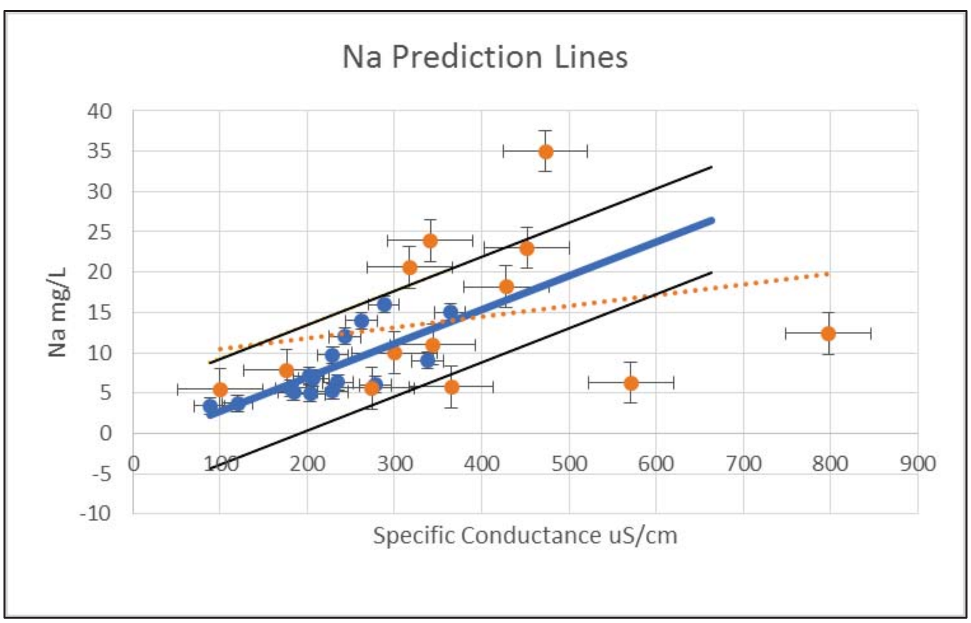


Figure 11a. Relation between Na ion concentration and specific conductance, 1960s and 1990s in Middle Passaic River Basin, New Jersey.

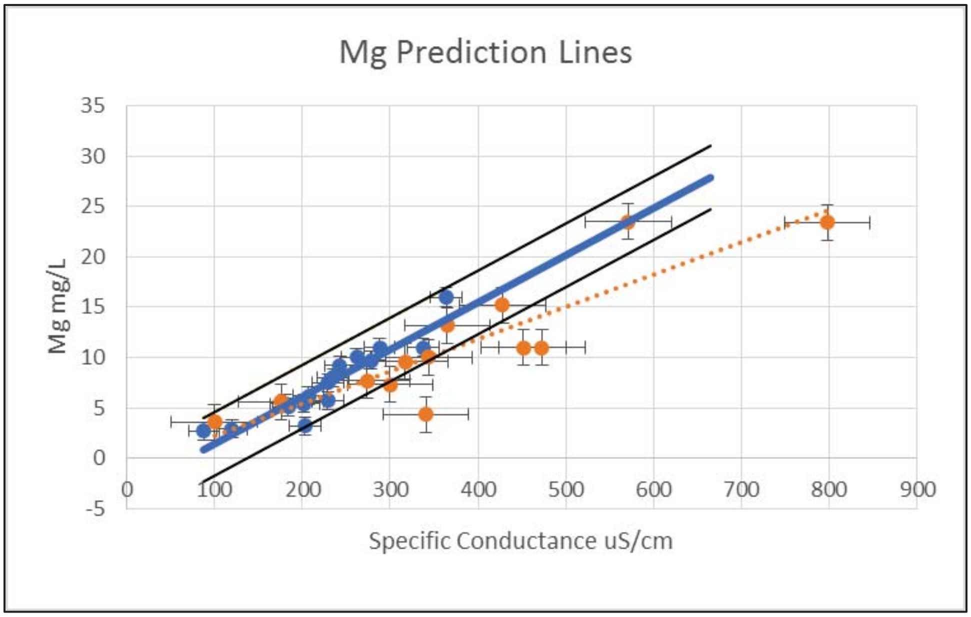


Figure 11b. Relation between Mg ion concentration and specific conductance, 1960s and 1990s in Middle Passaic River Basin, New Jersey.

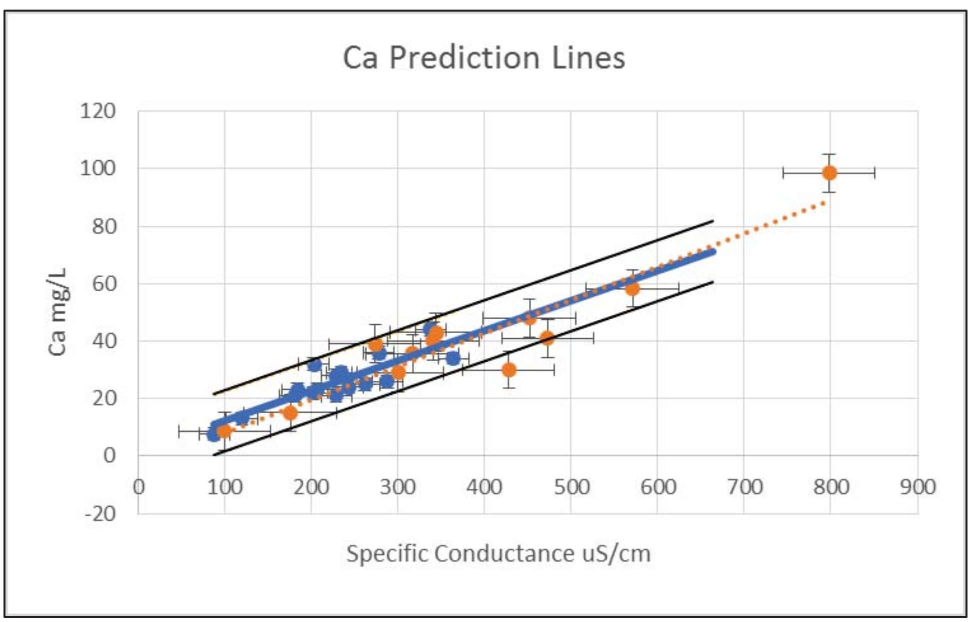


Figure 11c. Relation between Ca ion concentration and specific conductance, 1960s and 1990s in Middle Passaic River Basin, New Jersey.

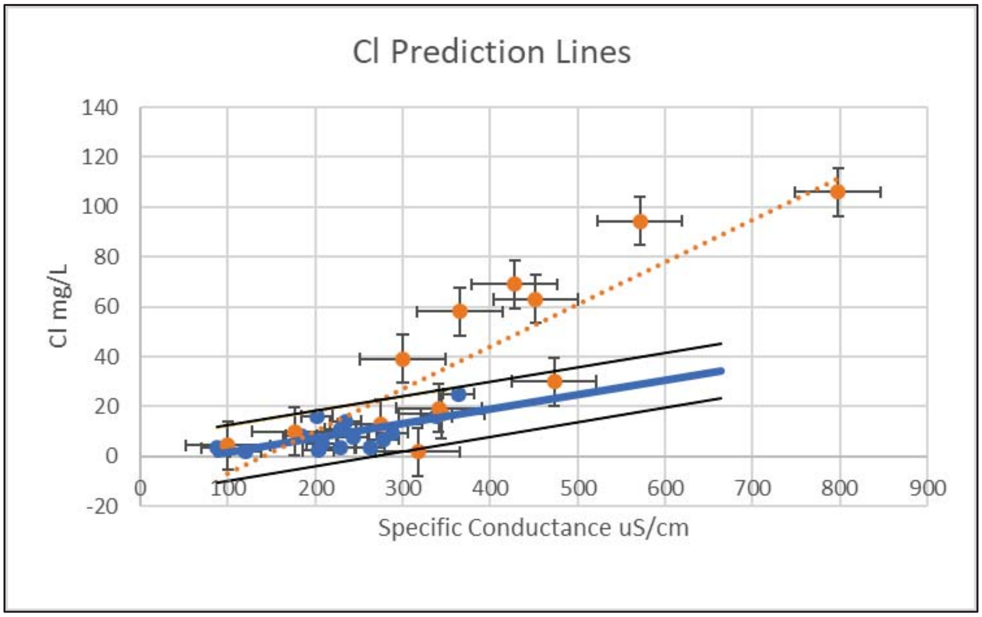


Figure 11d. Relation between Cl ion concentration and specific conductance, 1960s and 1990s in Middle Passaic River Basin, New Jersey.

3.1.3 MPRB Bivariate Analysis

Table 5 shows ion correlation coefficients, r, and coefficients of determination, r^2, for each decade and for the cumulative dataset. An increasing trend in correlation can be seen for Cl vs Na as well as Ca vs Mg. The linear correlations between these ions are displayed in Figures 12a-12e.

Ca and Mg (r^2 = 0.82, n = 127) have strong correlation, assumed to be caused by calcite erosion surrounding the study area being transported by major rivers such as the Pompton River. Na vs Ca (r^2 = 0.40, n = 124) and Cl vs Ca (r^2 = 0.47, n = 130) have weak correlation, indicating Na ions and Cl ions relations with Ca ions are minimal. Cl vs TDS (r^2 = 0.10, n = 124) and Na vs Cl (r^2 = 0.03, n = 124) show no significant correlation, signifying that the road salt ions Na and Cl have weak correlation with each other and Cl has no influence on TDS.

Table 5. Regression analysis correlation relationships for major ions in the Middle Passaic River Basin, New Jersey (in mg/L).

Y-dependant variable	X-independant variable	Decades	Pearson's r	r^2	n
Ca	Mg	60s	0.62	0.38	17
		80s	0.74	0.55	86
		90s	0.94	0.88	17
		00s	0.99	0.98	7
		Cumulative*	0.91	0.82	127
Na	Cl	60s	0.38	0.14	17
		80s	0.56	0.31	83
		90s	-0.04	0.00	17
		00s	0.73	0.53	7
		Cumulative*	0.17	0.03	124
Cl	Ca	60s	0.51	0.26	17
		80s	0.6	0.36	86
		90s	0.28	0.08	17
		00s	0.93	0.86	10
		Cumulative*	0.69	0.47	130
Na	Ca	60s	0.29	0.08	17
		80s	0.33	0.11	83
		90s	0.82	0.67	17
		00s	0.87	0.76	7
		Cumulative*	0.63	0.40	124
Cl	TDS	60s	0.66	0.44	17
		80s	0.68	0.46	86
		90s	0.17	0.03	17
		00s	0.99	0.98	4
		Cumulative*	0.32	0.10	124

*Calculated using all data (1960s-2000s).

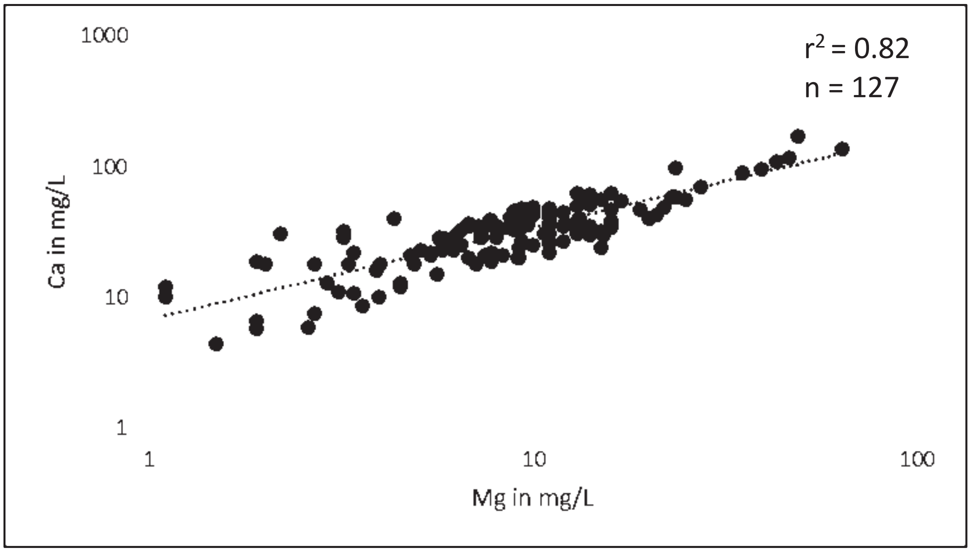


Figure 12a. Relation between Ca and Mg concentrations for samples collected from the 1960s through the 2010s in the Middle Passaic River Basin, New Jersey.

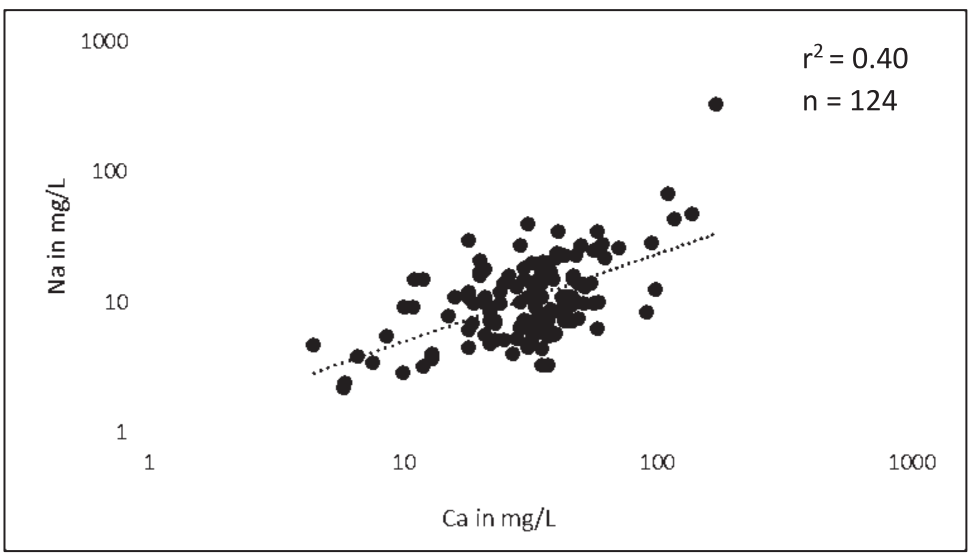


Figure 12b. Relation between Na and Ca concentrations for samples collected from the 1960s through the 2010s in the Middle Passaic River Basin, New Jersey.

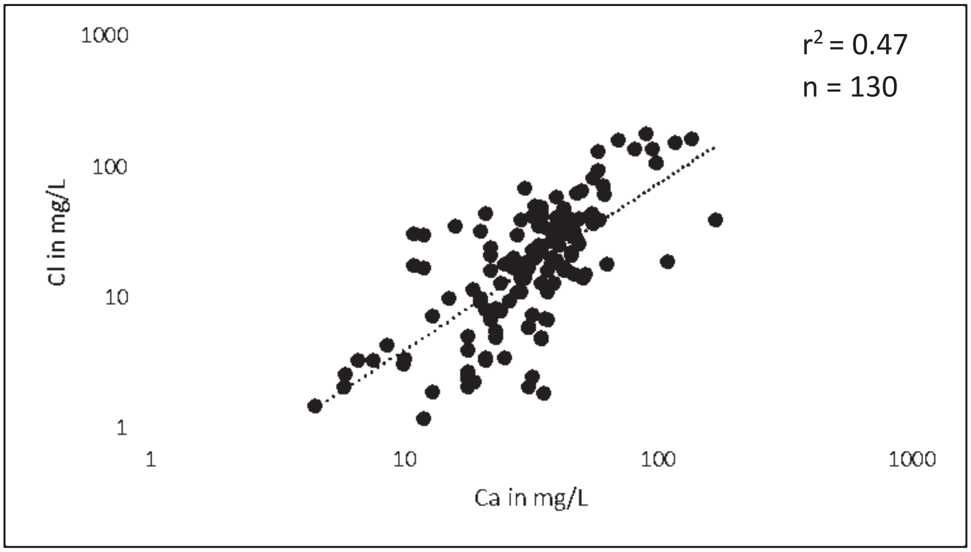


Figure 12c. Relation between Cl and Ca concentrations for samples collected from the 1960s through the 2010s in the Middle Passaic River Basin, New Jersey.

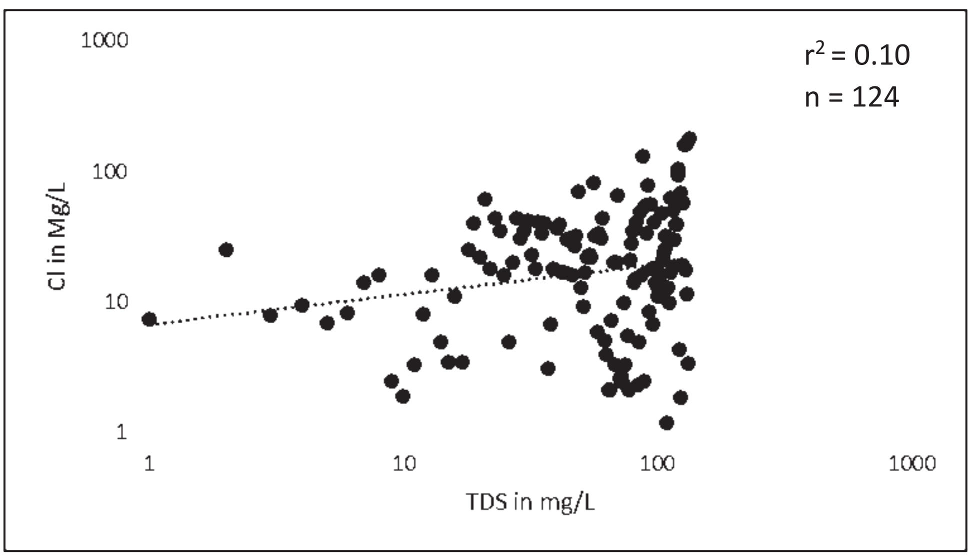


Figure 12d. Relation between Cl and total dissolved solids (TDS) concentrations for samples collected from the 1960s through the 2010s in the Middle Passaic River Basin, New Jersey.

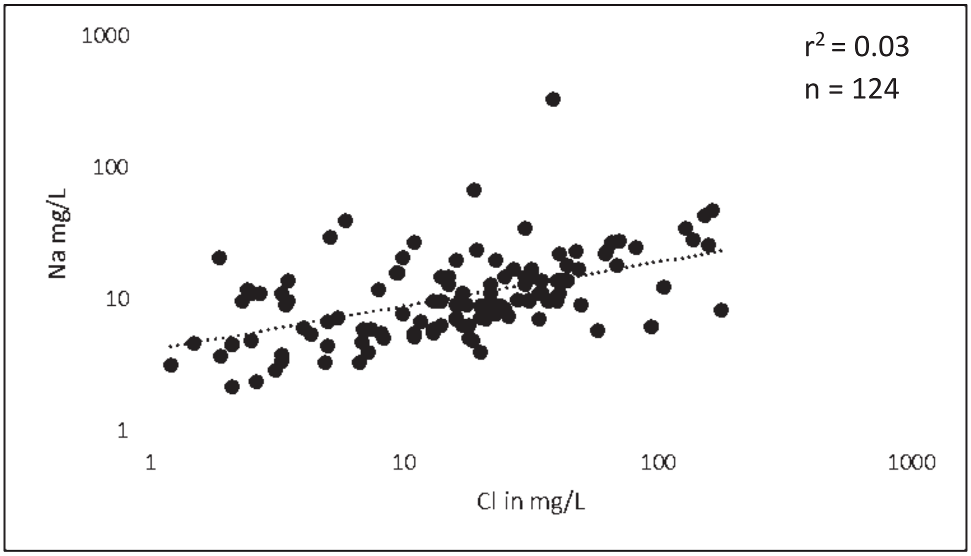


Figure 12e. Relation between Na and Cl concentrations for samples collected from the 1960s through the 2010s in the Middle Passaic River Basin, New Jersey.

3.1.4 MPRB Groundwater Species

The piper diagrams depict the groundwater ion composition for the MPRB in the 1960s to be $CaHCO_3$ based. The groundwater ion composition shows little to no observable fluctuation throughout time (Figures 13a-13e). The $CaHCO_3$ composition of the water, along with a TDS concentration below 1000 mg/L suggests fresh water in the area (Freeze & Cherry, 1979). The results imply that the amounts NaCl and $CaCl_2$ application in the MPRB have had little influence on the associated groundwater composition.

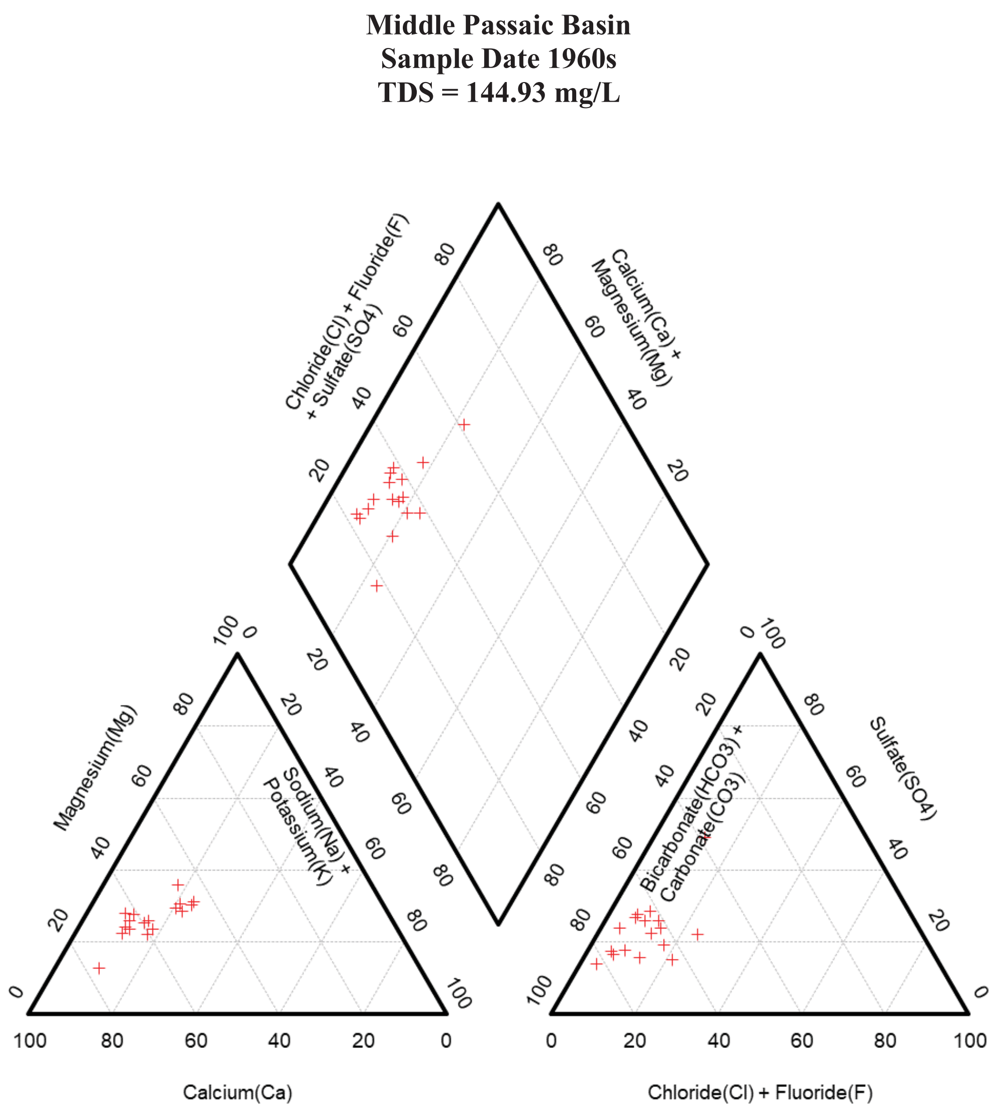


Figure 13a. Piper diagram showing the chemistry of the Middle Passaic River Basin in the 1960s.

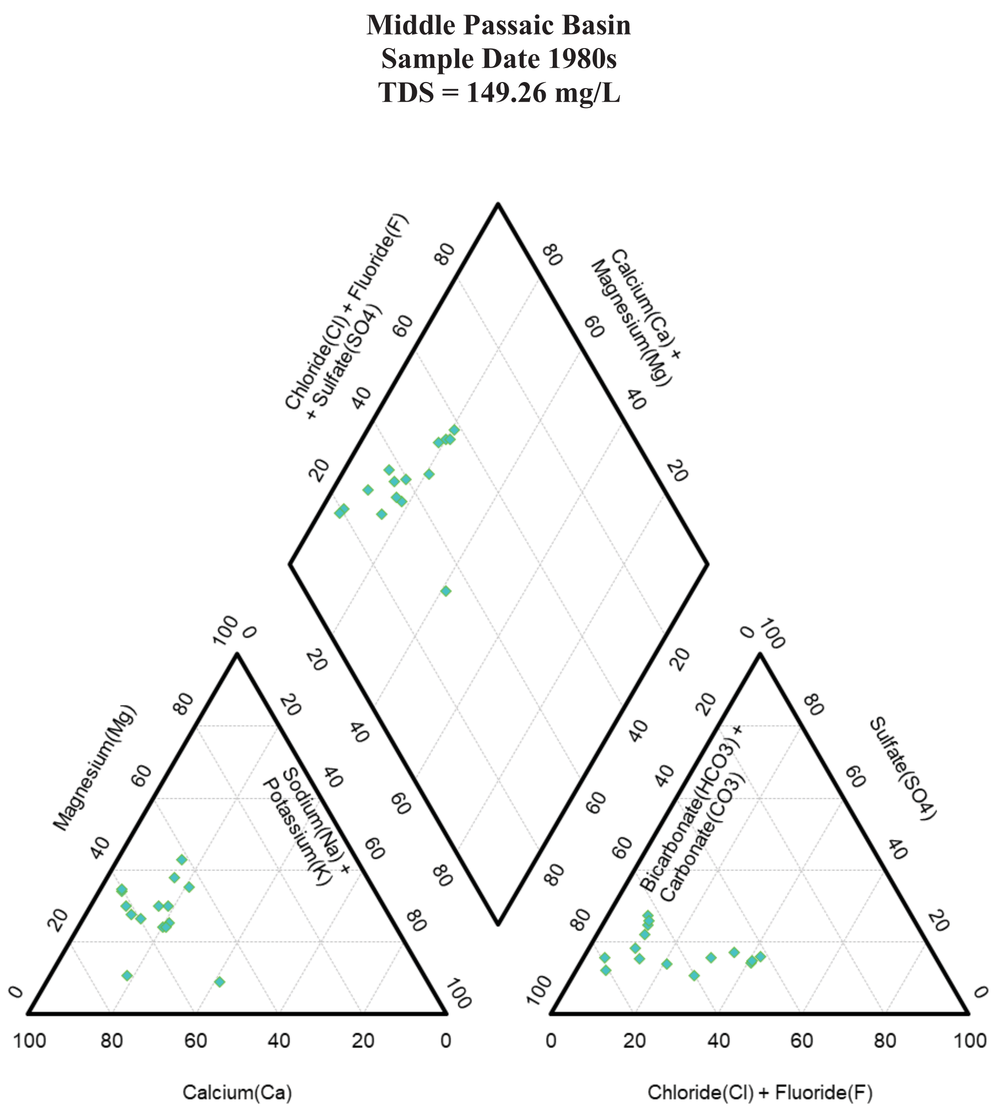


Figure 13b. Piper diagram showing the chemistry of the Middle Passaic River Basin in the 1980s.

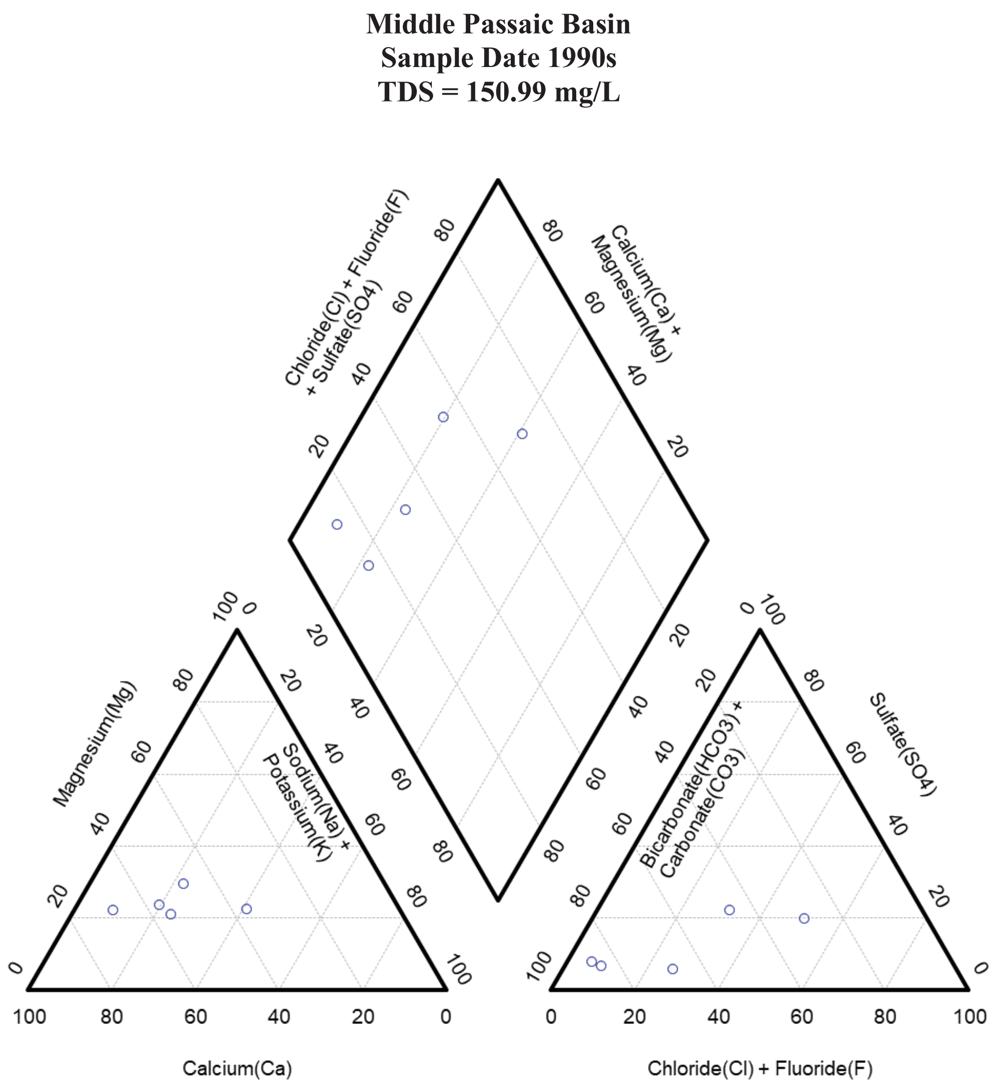


Figure 13c. Piper diagram showing the chemistry of the Middle Passaic River Basin in the 1990s.

Middle Passaic Basin
Sample Date 2000s
TDS = 156.18 mg/L

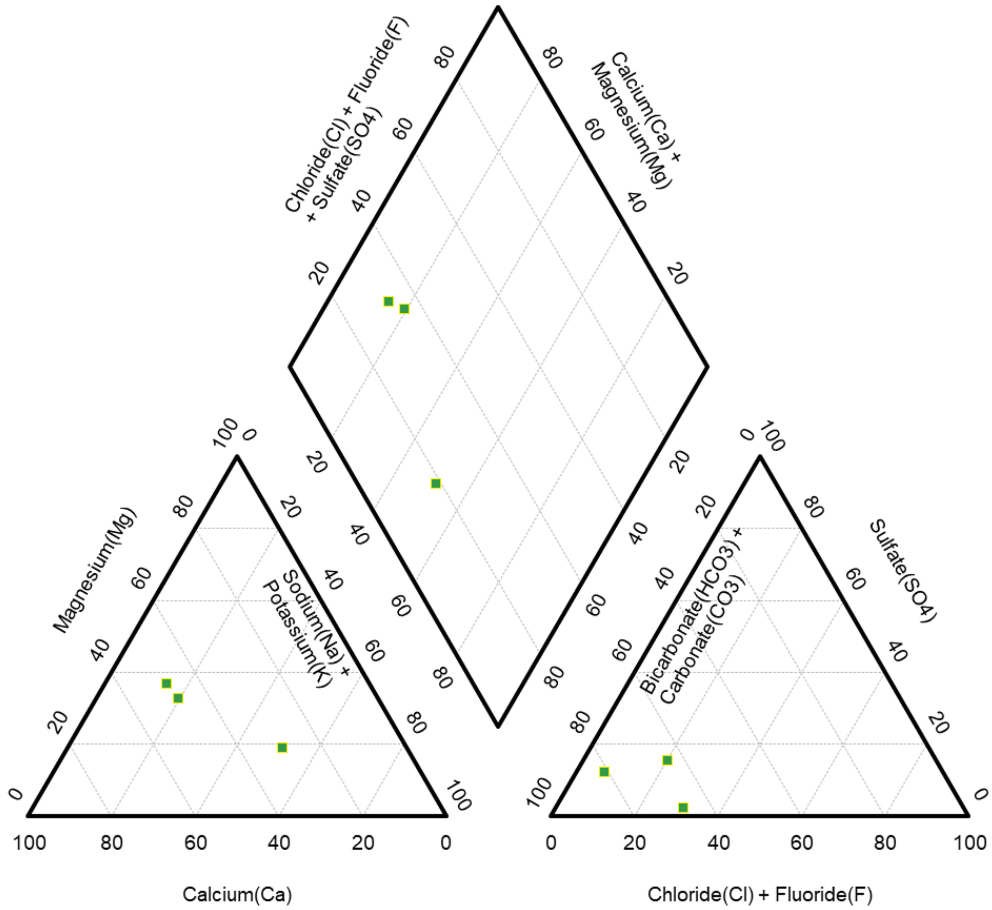


Figure 13d. Piper diagram showing the chemistry of the Middle Passaic River Basin in the 2000s.

Middle Passaic Basin
Sample Date 2010s
TDS = 160* mg/L

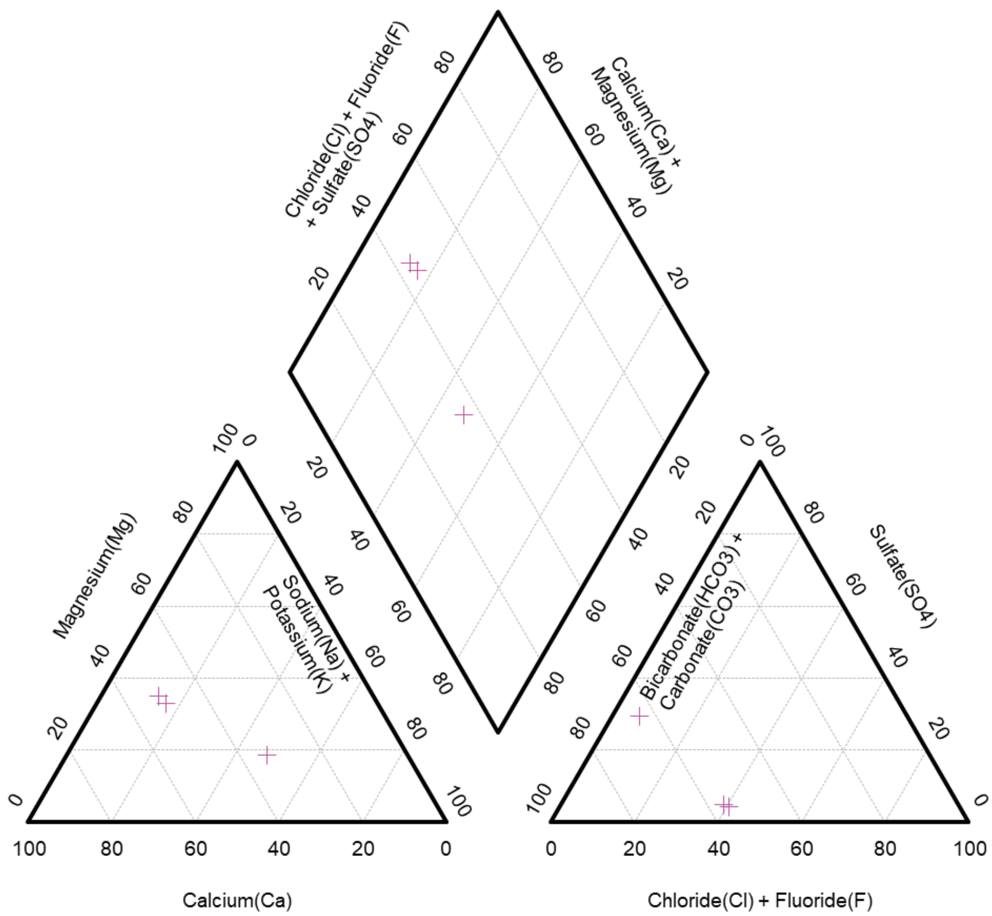


Figure 13e. Piper diagram showing the chemistry of the Middle Passaic River Basin in the 2010s. *Projected TDS.

3.2 Lower Passaic River Basin Results

3.2.1 LPRB Time Series and Schoeller Graphical Analysis

Significant concentration increases over time can be seen for Cl, Na, Ca, and TDS (Figures 14a, 14b, 14c, 14d). There is no significant increasing trend for Mg (Figure 14e). The observable increasing trend for Ca, Na, and Cl is significant enough to support a hypothesis that there is an anthropogenic source for these ions. The increasing TDS trend is also likely related to the road salt contamination of the groundwater.

Had the major ion sources been solely caused by domestic rock weathering, Mg and Ca ion concentrations would have increased at similar rates over time. Therefore, since the Mg and Ca ions increase at drastically different rates, they are presumably introduced into the groundwater from various sources.

The Schoeller plot helps visualize the magnitude of increase for the three ion concentrations: Cl concentrations increased by a magnitude of ≈15, Na by ≈11, and Ca by ≈3 (Figure 15). It is postulated that the anthropogenic application of NaCl and, to a lesser extent, $CaCl_2$ are the cause for the observable ion increases. Table 6 depicts the mean, standard deviation, and range of the ion concentrations from the 1960s to the 2010s.

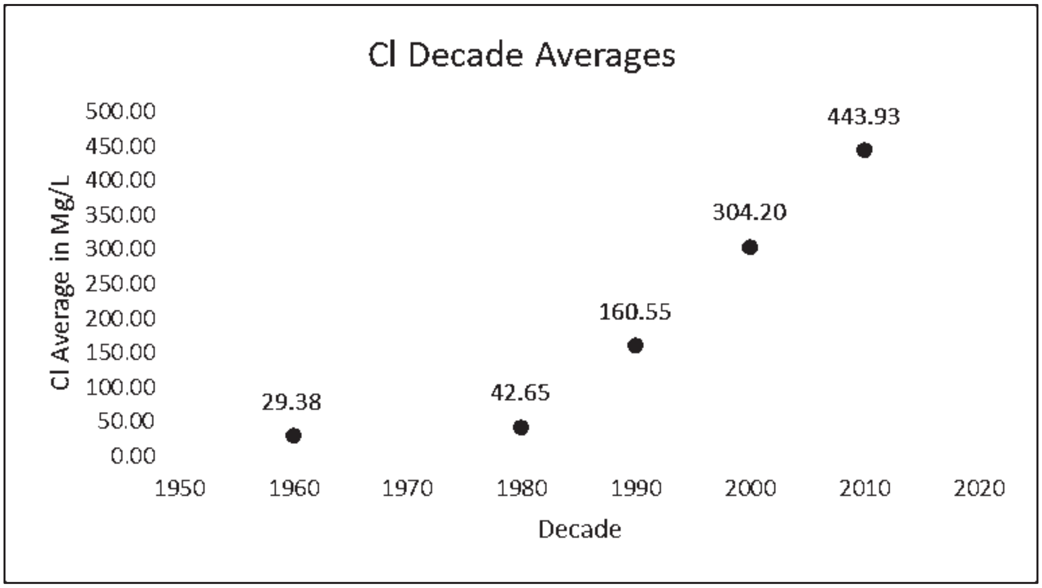


Figure 14a. Cl ion concentration averages for each decade, 1960s-2000s in the Lower Passaic River Basin, New Jersey (1970s data not available).

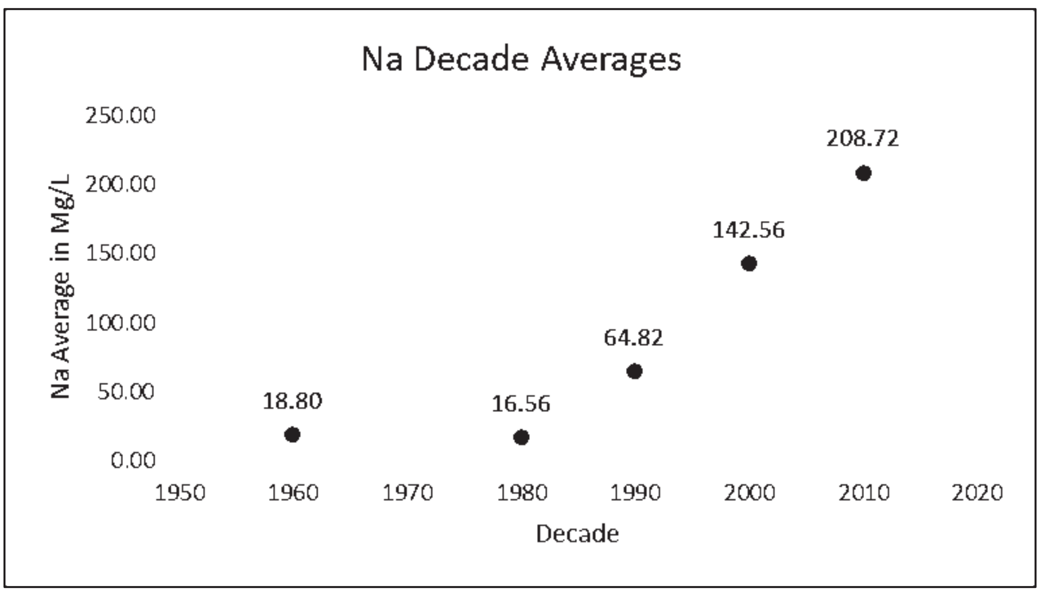


Figure 14b. Na ion concentration averages for each decade, 1960s-2000s in the Lower Passaic River Basin, New Jersey (1970s data not available).

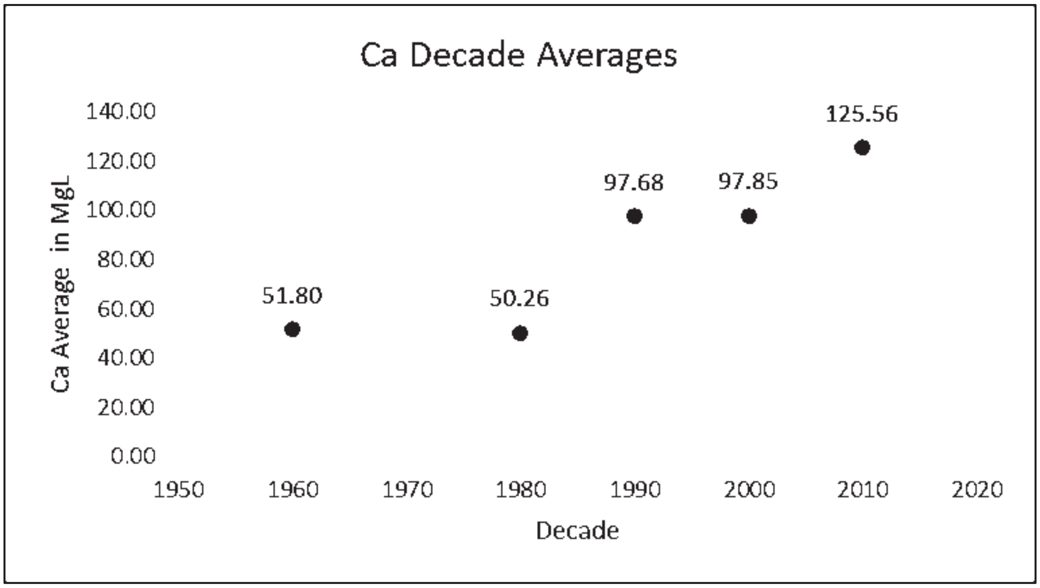


Figure 14c. Ca ion concentration averages for each decade, 1960s-2000s in the Lower Passaic River Basin, New Jersey (1970s data not available).

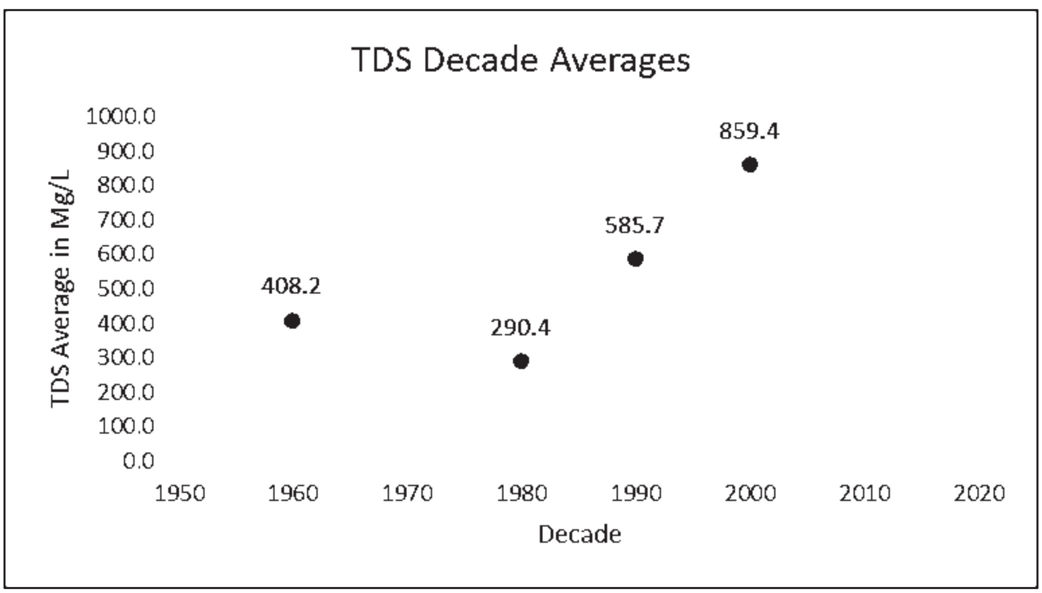


Figure 14d. Total dissolved solid concentration averages for each decade, 1960s-2000s in the Lower Passaic River Basin, New Jersey (1970s data not available).

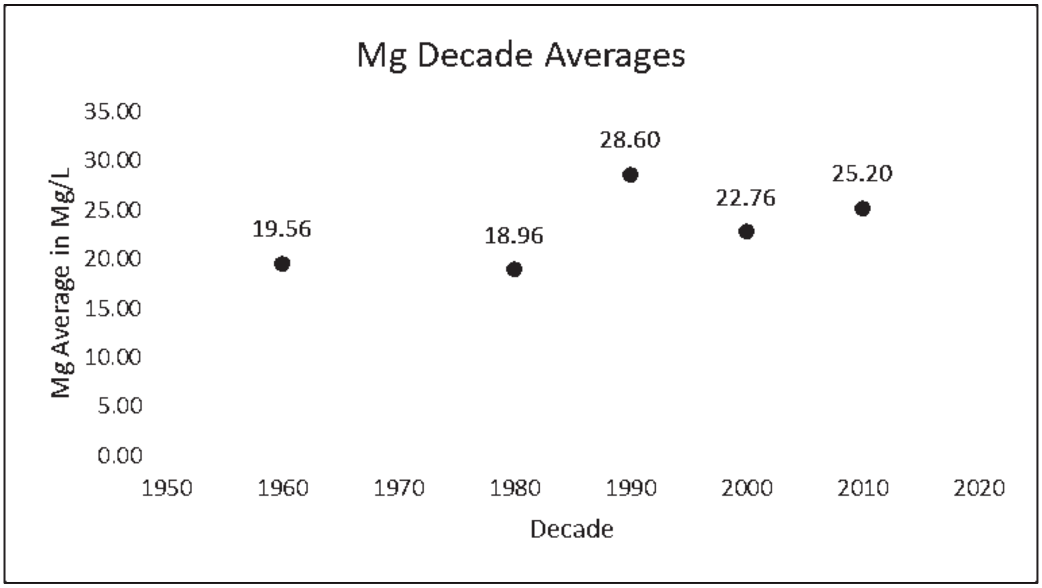


Figure 14e. Mg ion concentration averages for each decade, 1960s-2000s in the Lower Passaic River Basin, New Jersey (1970s data not available).

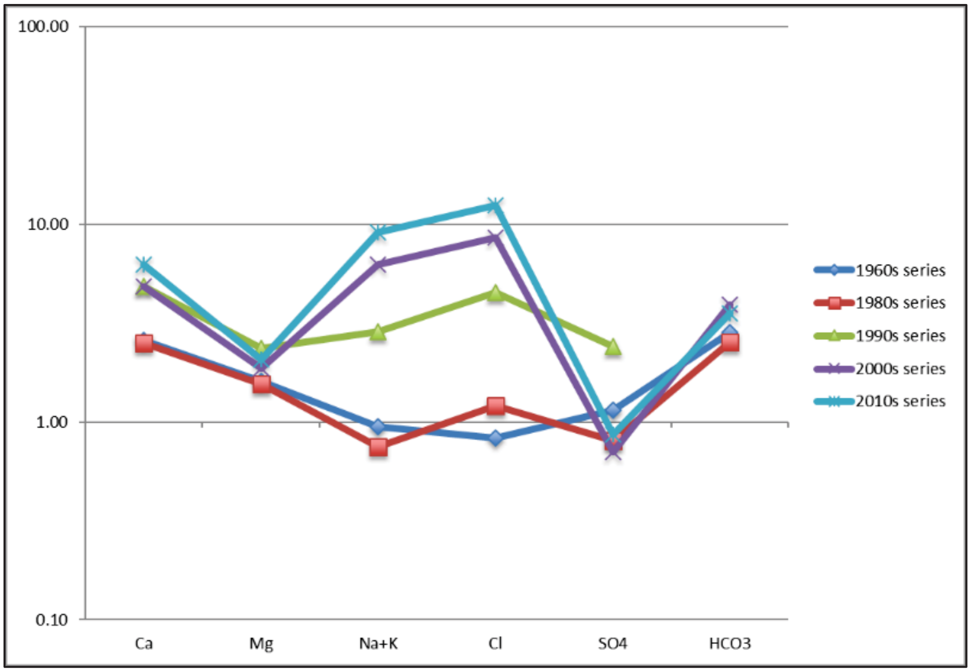


Figure 15. A Schoeller depicting log (concentration) of major ions for the 1960s, 1980s, 1990s, 2000s, and 2010s in the Lower Passaic River Basin, New Jersey.

Table 6. Mean, standard deviation, range, and data count of major ion concentration and total dissolved solids, Lower Passaic River Basin, New Jersey (concentrations are in mg/L).

Ion	Decade	Mean	SD	Max	Min	Count
Na^+	1960s	18.80	11.30	36.00	9.00	5
	1980s	16.56	8.77	54.00	8.10	34
	1990s	64.82	74.81	238.00	13.00	13
	2000s	142.56	215.36	779.00	8.39	14
	2010s	208.72	175.45	607.00	28.60	10
Mg^{2+}	1960s	19.56	12.30	34.00	0.80	5
	1980s	18.96	8.53	44.00	8.60	34
	1990s	28.60	21.12	72.70	8.20	13
	2000s	22.76	9.74	40.60	10.60	14
	2010s	25.20	9.65	37.40	10.90	10
Ca^{2+}	1960s	51.80	29.90	82.00	12.00	5
	1980s	50.26	20.98	99.00	14.00	34
	1990s	97.68	53.14	250.00	28.00	13
	2000s	97.85	57.25	233.00	40.6	14
	2010s	125.56	64.62	248.00	30.00	10
Cl^-	1960s	29.38	19.29	54.00	3.60	8
	1980s	42.65	38.50	230.00	4.70	35
	1990s	160.55	234.72	738.00	28.00	13
	2000s	304.20	434.98	1580.00	30.50	14
	2010s	443.93	301.71	1120.00	87.30	10
TDS	1960s	411.86	153.51	566.31	242.70	4
	1980s	286.83	93.79	610.44	132.38	33
	1990s	588.37	471.50	1647.45	294.19	11
	2000s	860.50	914.33	3530.25	235.35	14
	2010s	-	-	-	-	-

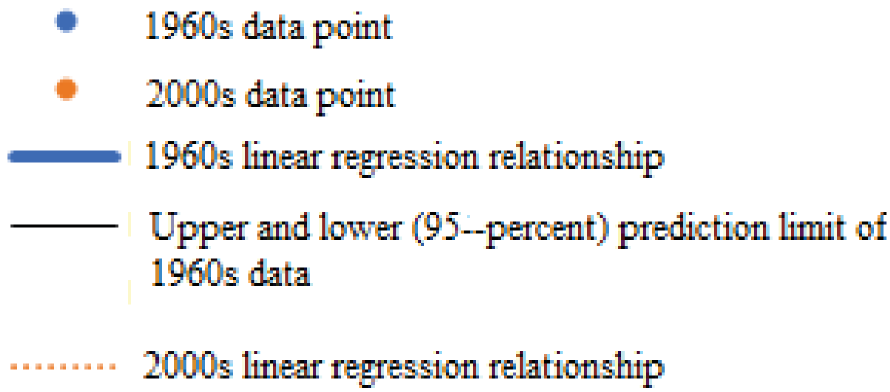
3.2.2 LPRB Prediction Intervals

Significant concentration increases are found for the ions Na (722.41%) and Cl (1062.89%) between the 1960s and 2000s (Table 7). Ca ions (105.81%) show concentration increases within the same timeframe to smaller degree. Additionally, linear regression analyses of Na and Cl (Figures 16a and 16b) depict concentration increases greatly above the prediction intervals. Ca comparisons are within prediction (Figure 16c), and Mg (Figure 16d) falls below prediction. The results of the regression analyses for LPRB support the hypothesis that Na and Cl concentrations in groundwater are presently increasing at a higher rate as compared to other major ions. Ca ionsis contaminating the groundwater at a statistically greater rate than Mg ions, indicating that Ca ions may be stemming from an outside source such as $CaCl_2$.

Table 7. Calculated mean yield of major ion concentrations from Lower Passaic River Basin, New Jersey (all yields are in mg/L).

Constituent	1960s	2000s	Difference	Percent Increase
Sodium (Na)	18.8	154.61	135.81	722.41%
Potassium (K)	4.90	2.36	-2.54	-51.82%
Magnesium (Mg)	19.56	24.87	5.31	27.15%
Calcium (Ca)	51.80	106.61	54.81	105.81%
Chloride (Cl)	29.38	341.60	312.23	1062.89%
Sulfate (SO4)	55.17	37.04	-18.12	-32.85%
Bicarbonate (HCO3)	172.63	219.82	330.35	191.37%

Legend



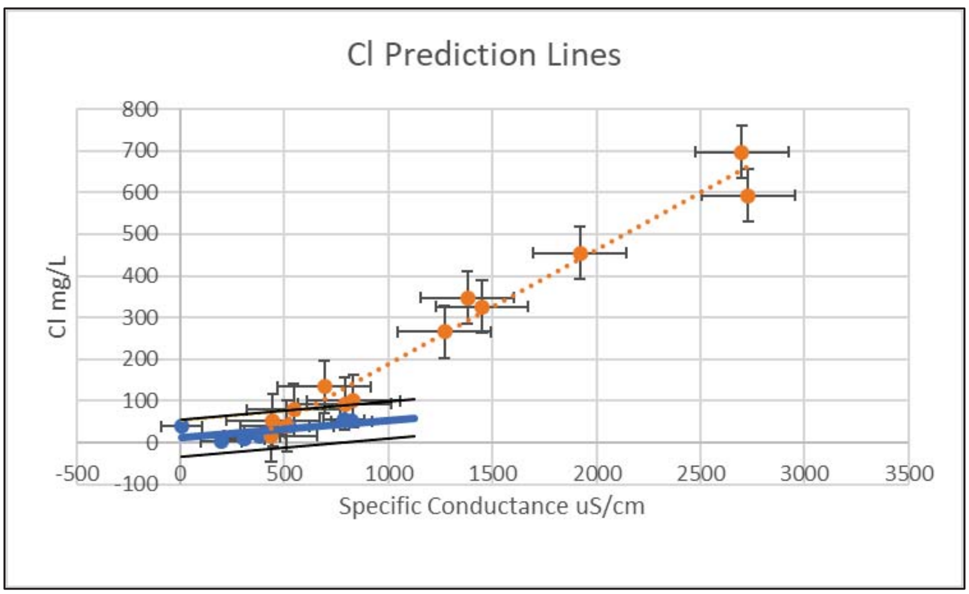


Figure 16a. Relation between Cl ion concentration and specific conductance, 1960s and 2000s in Lower Passaic River Basin, New Jersey.

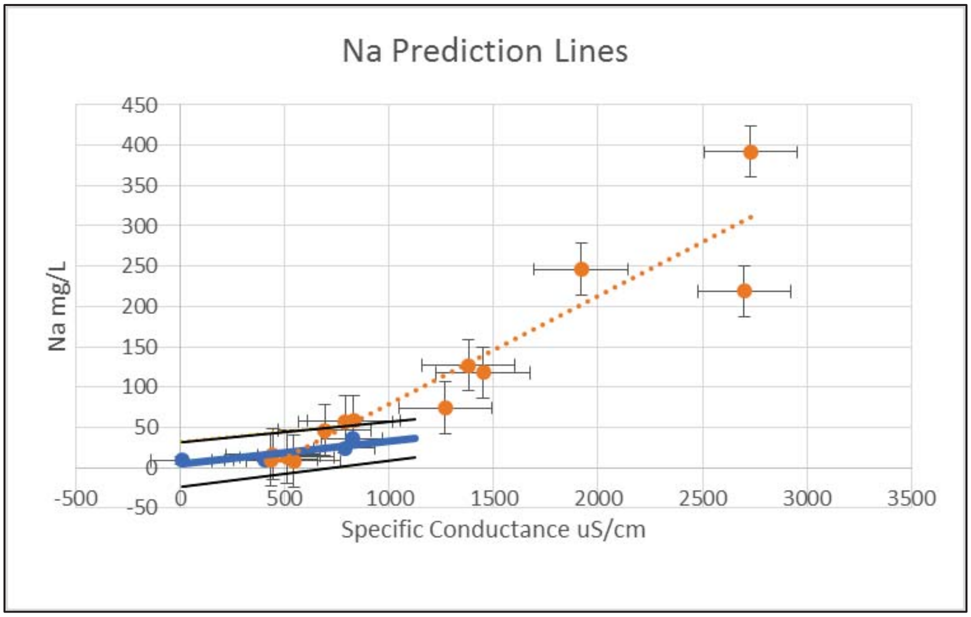


Figure 16b. Relation between Na ion concentration and specific conductance, 1960s and 2000s in Lower Passaic River Basin, New Jersey.

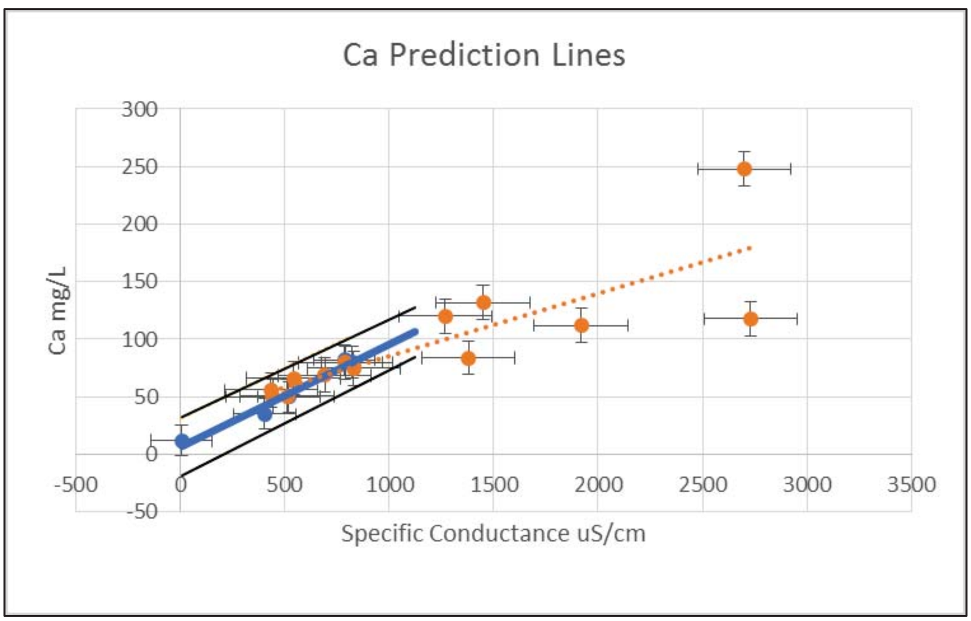
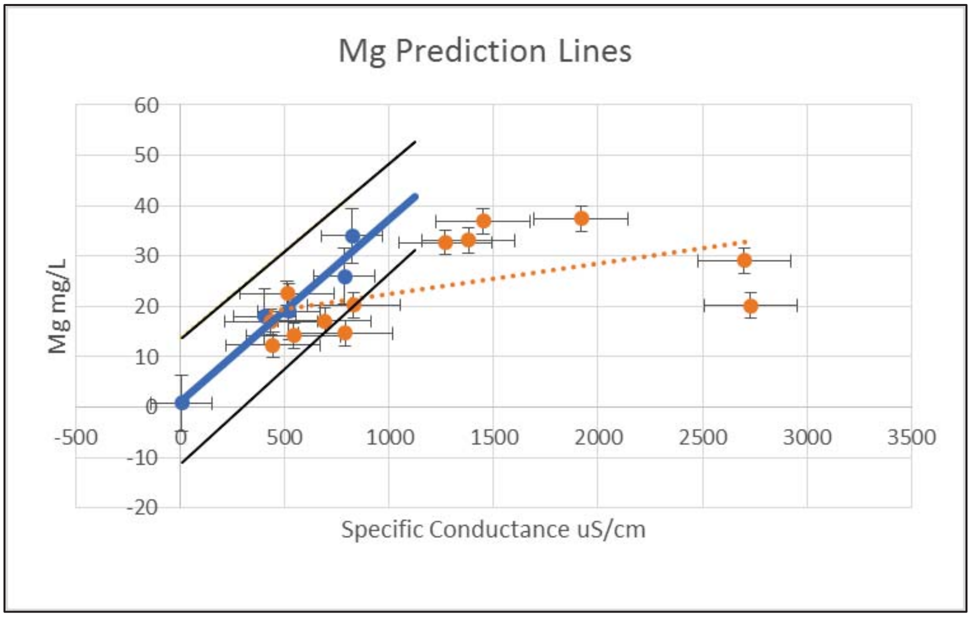


Figure 16c. Relation between Ca ion concentration and specific conductance, 1960s and 2000s in Lower Passaic River Basin, New Jersey.



Figures 16d. Relation between Mg ion concentration and specific conductance, 1960s and 2000s in Lower Passaic River Basin, New Jersey.

3.2.3 LPRB Bivariate Analysis

A visual representation of the linear correlations for the cumulative LPRB variables is shown in Figures 17a-17e, while the r^2 values of the bivariate relationships throughout time are in Table 8. The correlation between Ca and Mg observably decreases throughout the study period. In the LPRB sedimentary rock, the $CaHCO_3$ groundwater species should be dominant and a Ca and Mg relationship should remain consistent (Fetter, 2014). Therefore, the decreasing correlation between these ions from the 1960s to the 2010s implies an external Ca contaminant, likely caused by liquid $CaCl_2$ application. Although there was an observable decrease in correlation through time, the overall cumulative dataset for Ca vs Mg ($r^2 = 0.79$, n = 76) show strong correlation. This strong overall relation between the two ions signifies a core foundation which stems from an identical geological source.

Contrary to the MPRB ion analysis, the LPRB results show that Na vs Cl ($r^2 = 0.78$, n = 76) have strong correlation, indicating that they are coming from the same source. Cl vs Ca ($r^2 = 0.62$, n = 76) have a relatively strong correlation, also indicating these ions may be from identical sources as one another. Na vs Ca ($r^2 = 0.23$, n = 76) have very weak correlation, indicating that they are stemming from different origins. Cl vs TDS ($r^2 = 0.19$, n = 62) shows weak correlation as well, indicating an unexpected lack of Cl influence on TDS. The relationship between Cl and TDS is likely being obscured by large amounts of various other pollutants which are associated with industrial and urban storm water runoff (Riva-Murray, Riemann et al., 2010). The results of the LPRB bivariate analyses strongly support the hypothesis that heavy NaCl and $CaCl_2$ application is contaminating the groundwater in highly urbanized areas.

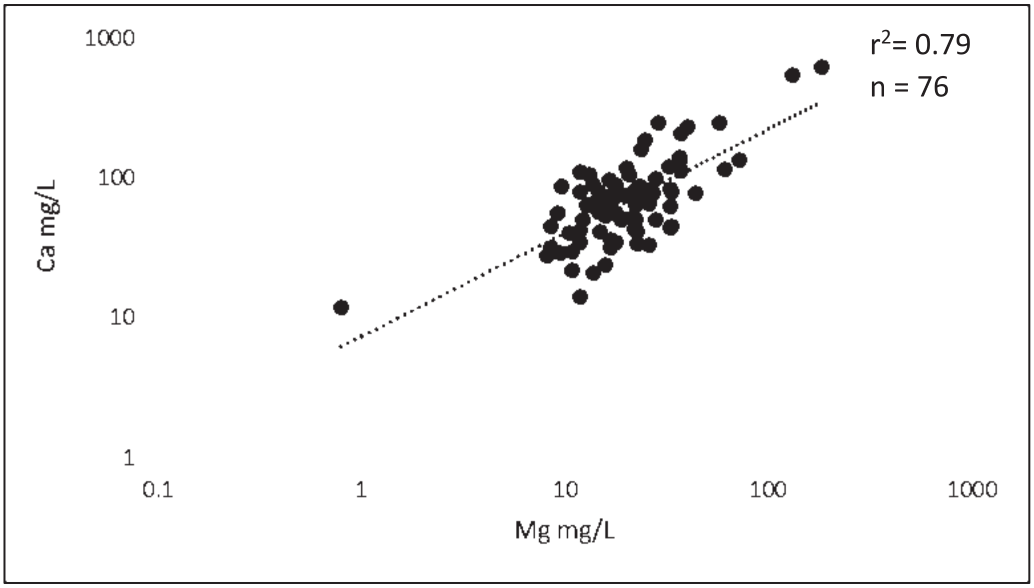


Figure 17a. Relation between Ca and Mg concentrations for samples collected from the 1960s through the 2010s in the Lower Passaic River Basin, New Jersey.

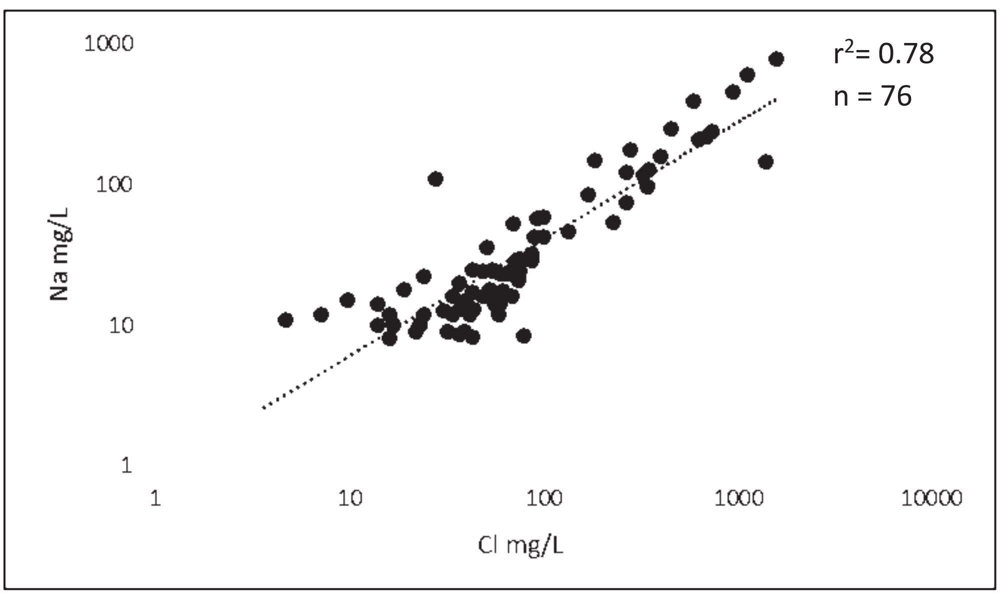


Figure 17b. Relation between Na and Cl concentrations for samples collected from the 1960s through the 2010s in the Lower Passaic River Basin, New Jersey.

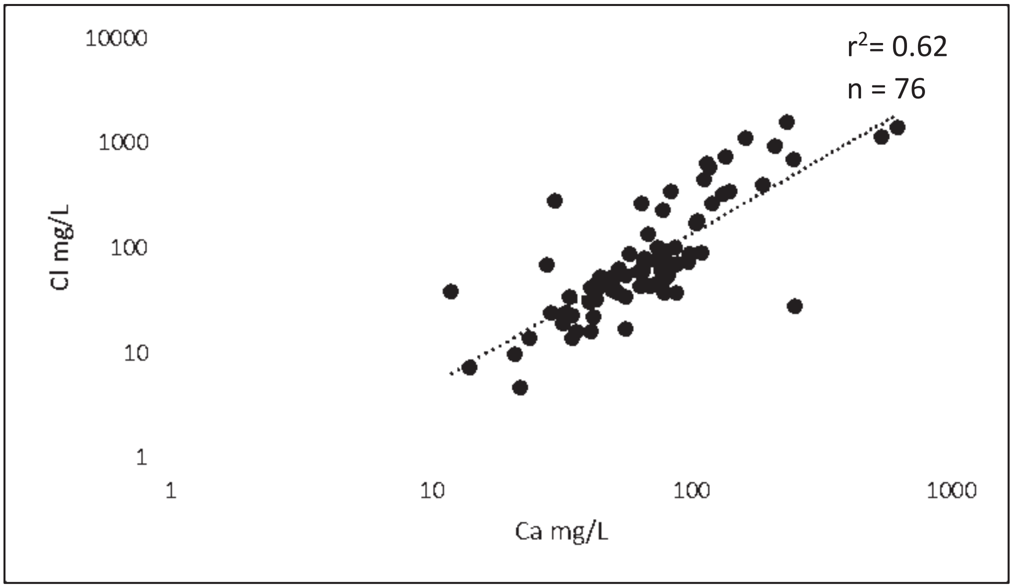


Figure 17c. Relation between Cl and Ca concentrations for samples collected from the 1960s through the 2010s in the Lower Passaic River Basin, New Jersey.

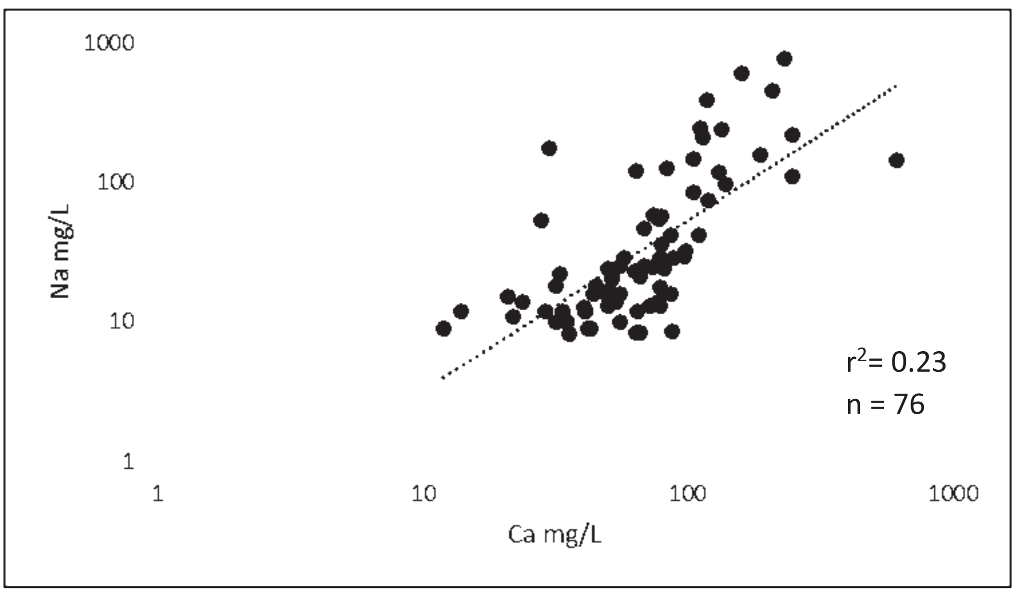


Figure 17d. Relation between Na and Ca concentrations for samples collected from the 1960s through the 2010s in the Lower Passaic River Basin, New Jersey.

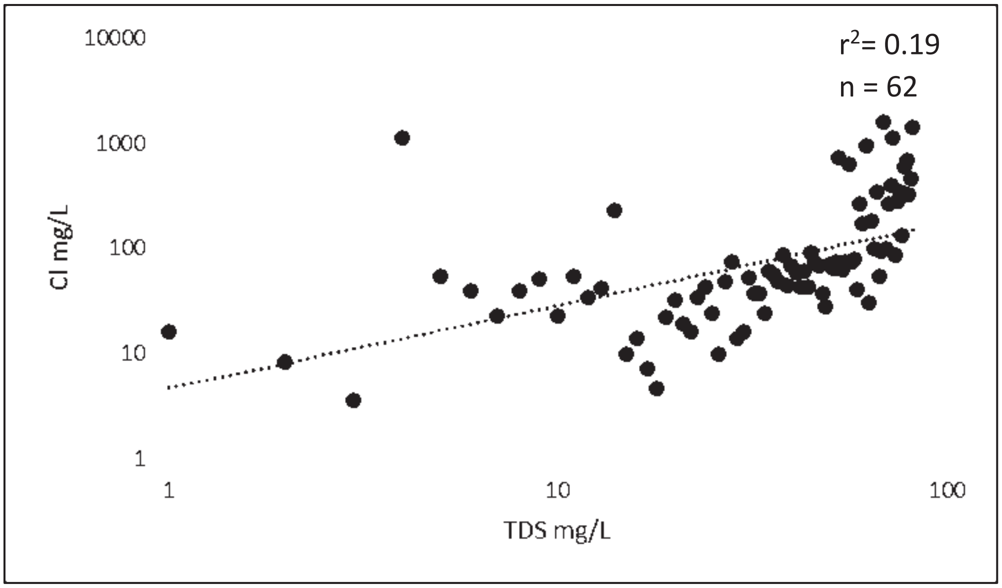


Figure 17e. Relation between Cl and total dissolved solids (TDS) concentrations for samples collected from the 1960s through the 2010s in the Lower Passaic River Basin, New Jersey.

Table 8. Regression analysis correlation relationships for major ions in the Lower Passaic River Basin, New Jersey (in mg/L).

Y-dependant variable	X-independant variable	Decades	Pearson's r	r^2	n
Ca	Mg	60s	0.94	0.88	5
		80s	0.28	0.08	34
		90s	0.67	0.45	13
		00s	0.79	0.62	14
		10s	0.55	0.30	10
		Cumulative*	0.89	0.79	76
Na	Cl	60s	0.76	0.58	5
		80s	0.84	0.71	34
		90s	0.93	0.86	13
		00s	0.99	0.98	14
		10s	0.93	0.86	10
		Cumulative*	0.88	0.78	76
Cl	Ca	60s	0.72	0.52	5
		80s	0.62	0.38	34
		90s	0.20	0.04	13
		00s	0.93	0.86	14
		10s	0.61	0.37	10
		Cumulative*	0.79	0.62	76
Na	Ca	60s	0.88	0.77	5
		80s	0.41	0.17	34
		90s	0.48	0.23	13
		00s	0.93	0.86	14
		10s	0.32	0.10	10
		Cumulative*	0.48	0.23	76
Cl	TDS	60s	0.92	0.85	4
		80s	0.89	0.79	33
		90s	0.50	0.25	11
		00s	0.99	0.98	14
		10s	-	-	-
		Cumulative*	0.44	0.19	62

*Calculated using all data (1960s-2010s)

3.2.4 LPRB Groundwater Species

The groundwater ion composition of LPRB in the 1960s and 1980s was $Ca(HCO_3)_2$ based (Figures 18a and 18b). There was a lack of sufficient data for the 1990s, therefore a piper diagram for that decade could not be constructed. By the 2000s, there is an observable shift in water composition compared to previous decades and the hydrochemical characteristics of the groundwater show high concentrations of both $Ca(HCO_3)_2$ and NaCl (Figure 18c). In the 2010s, the groundwater composition is almost completely of the NaCl facies (Figure 18d). Overall, the piper diagrams for the LPRB groundwater facies depict a clear shift from being $Ca(HCO_3)_2$ dominant in the 1960s, to Ca-Na-Cl-HCO_3 in the 2000s, and NaCl in the 2010s. The fact that the shift in water composition occurred within a time span of 50 years, and that the TDS concentrations indicate freshwater suggests the change was a result of natural groundwater evolution processes.

Lower Passaic Basin
Sample Date 1960s
TDS = 408.2 mg/L

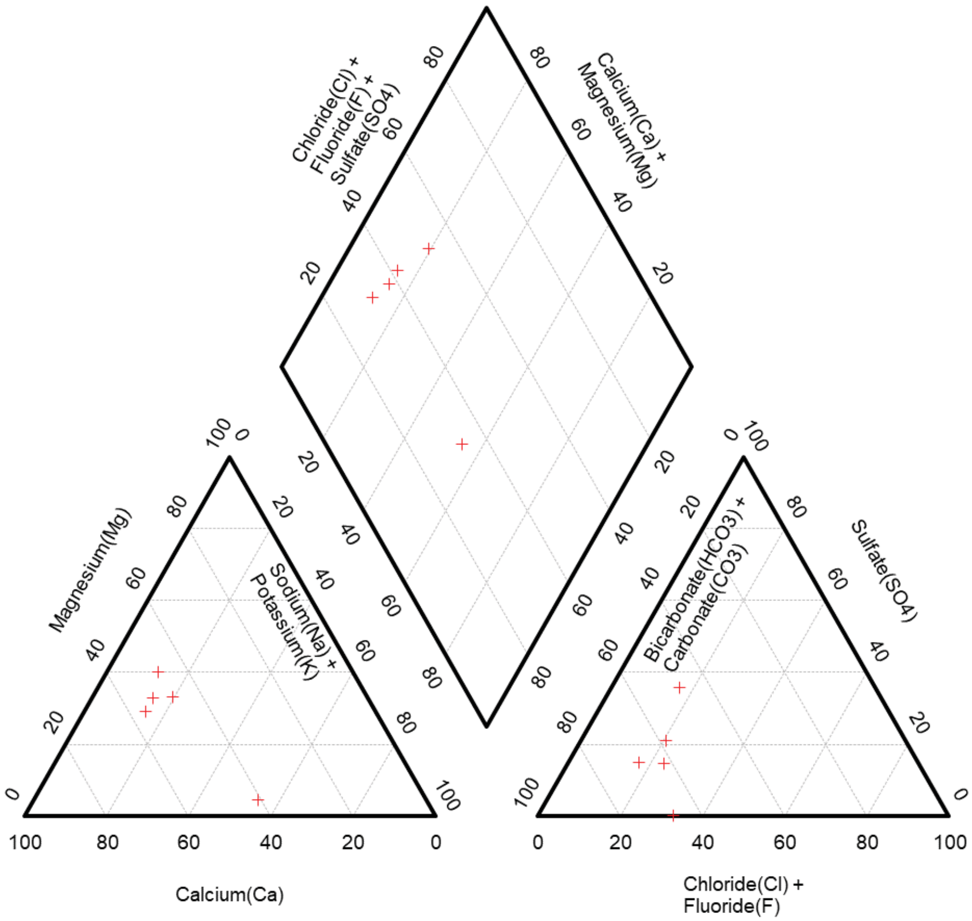


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Figure 18a. Piper diagram showing the chemistry of the Lower Passaic River Basin in the 1960s

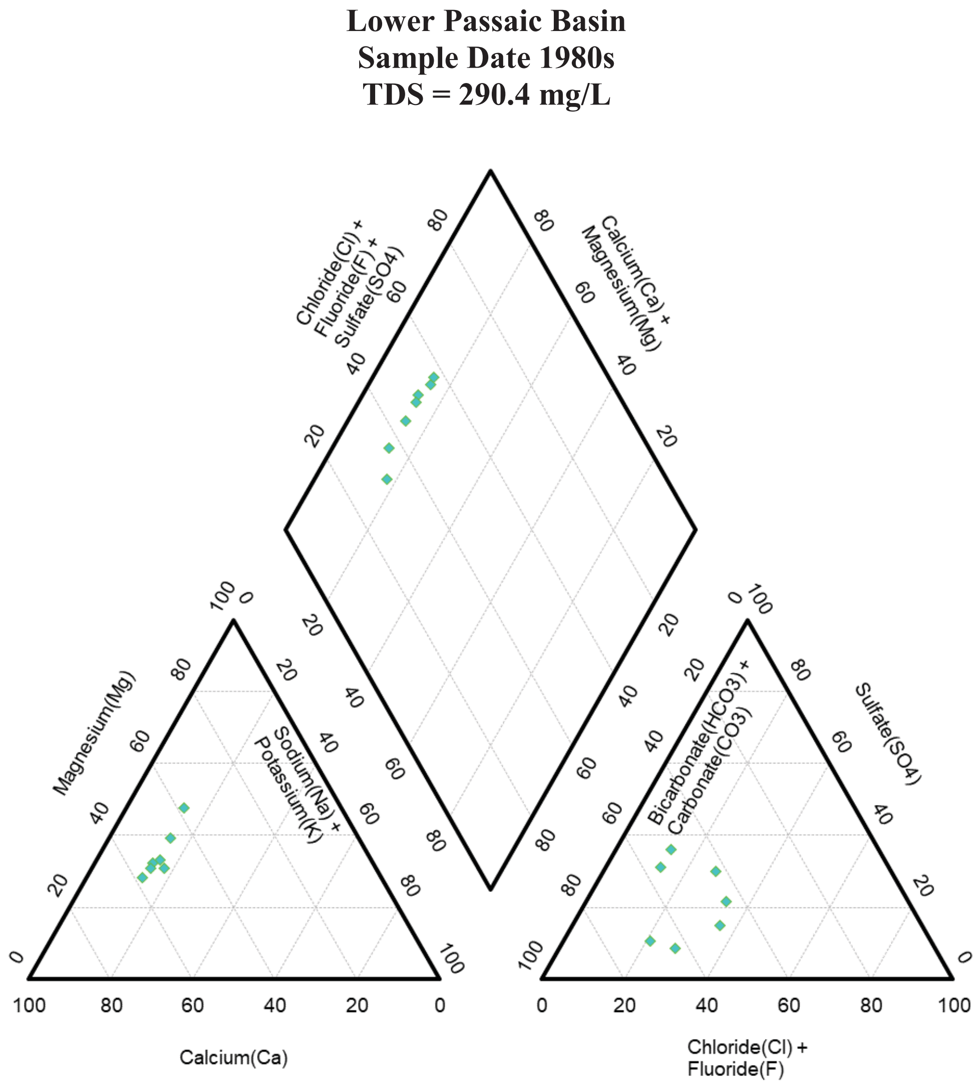

Figure 18b. Piper diagram showing the chemistry of the Lower Passaic River Basin in the 1980s.

Lower Passaic Basin
Sample Date 2000s
TDS = 859.4 mg/L

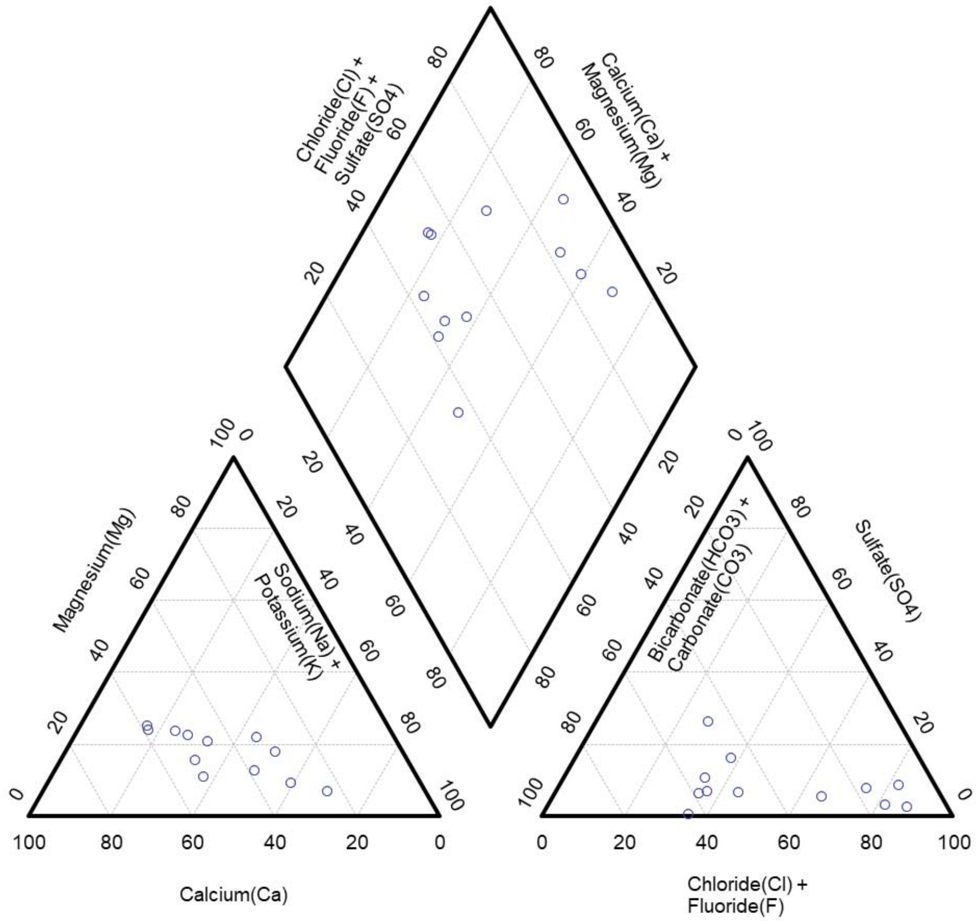

Figure 18c. Piper diagram showing the chemistry of the Lower Passaic River Basin in the 2000s.

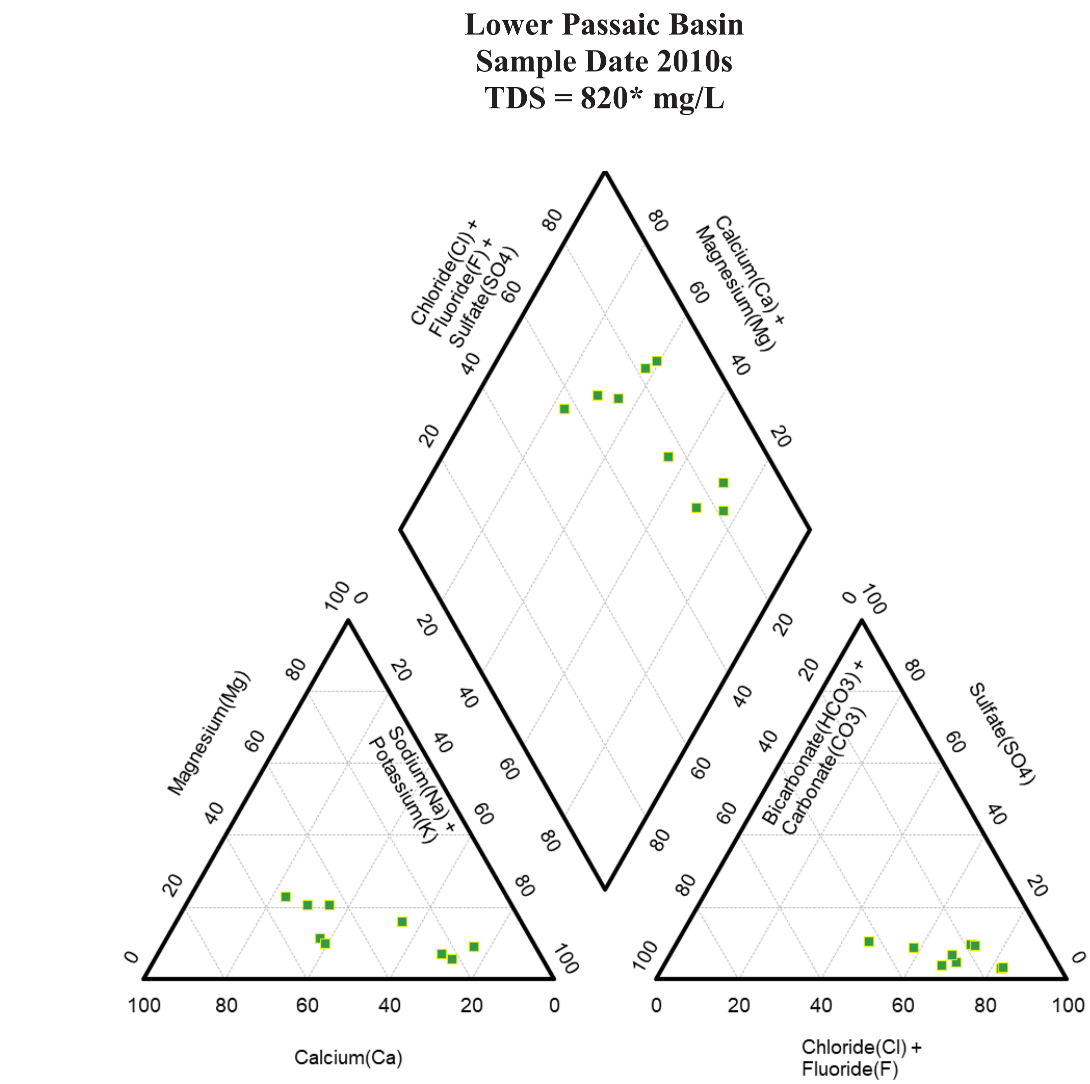

Figure 18d. Piper diagram showing the chemistry of the Lower Passaic River Basin in the 2010s. *Projected TDS.

3.3 MPRB and LPRB Potentiometric and Ion Concentration Maps

Hydraulic potentiometric maps depicting differentials in water table and groundwater flow give insight into potential ion sources (MPRB: Figures 19a-19d; LPRB: Figures 24a-24d). Groundwater flow could play a large role in the transportation of major ions, leading to ion accumulations in discharge zones. If these tools are used in conjunction with ion concentration maps, a visualization of ion transportation by means of groundwater flow can be observed (MPRB: Figures 20a-20d, 21a-21d, 22a-22d, 23a-23d; LPRB: Figures 25a-25d, 26a-26d, 27a-27d, 28a-28d). The maps provided in this study are restricted by the well locations, and therefore offer limited information on ion concentrations throughout the entire basin. Construction of the maps was also limited by well counts, therefore some decade maps were omitted due to lack of data. When comparing the ion concentration and potentiometric maps, there is little evidence indicative of a relationship between groundwater flow and ion concentrations. Thus, the advective flow of groundwater may not have played a significant role in the observed pattern of major ion distribution in the MPRB and LPRB.

4. Discussion

4.1 Middle Passaic River Basin

It is important to highlight that the MPRB contains the largest water reservoir in the State of New Jersey. The basin is also positioned on the North Eastern Piedmont, underlain by low-porosity metamorphic and igneous bedrock. Additionally, there is minimal deicing necessitated due to the scarcity of major roads in the region (NJDOT, 2018). The piper diagram results suggest that there has not been an observable statistical concentration increase in deicing ions Cl and Na for MPRB groundwater. Time series and Schoeller graphical analyses did not show significantly pronounced increasing trends in ion concentrations for Ca or Na. As a result, it can be concluded that deicing ions had an observably lesser impact on the MPRB compared to their effect on the LPRB. Based on environmental and anthropogenic factors, there are three proposed causes for this outcome:

1. The water reservoirs of the MPRB are serving as a diluting solution for the ion solutes, resulting in lower ion concentrations in well samples. The large volumes of surface water flowing through the superficial glacial rift of the region are potentially leaching the permeable upper layers and displacing the deicer ions downstream.

2. The low-porosity igneous and metamorphic bedrock of the region results in minimal geologic absorption rates for the deicing materials. These geologic factors could be preventing the ions from seeping into the ground, causing their continued advection through the surface waters.

3. The relatively low application of deicing materials in the MPRB (52.9 ton/sq. mi as compared to 167.4 tons/sq. mi in the LPRB) is not in sufficient quantities to have clear influence on the groundwater. This proposition is supported by the fact that there are insignificant bivariate correlations between the deicing salt ions Ca, Cl, and Na: Cl vs Ca ($r^2 = 0.47$, $n = 130$), Na vs Ca ($r^2 = 0.40$, $n = 124$), Na vs Cl ($r^2 = 0.03$, $n = 124$). The lack of bivariate correlation indicates that sodium chloride and calcium chloride are not major sources of contamination.

Cl uniquely showed distinct concentration increases in the time series and prediction interval statistical analyses. These results suggest that there is some measurable evidence for road deicing in the MPRB. Nevertheless, the lack of bivariate correlation between all three deicing ions offsets that hypothesis. It is therefore likely that Cl is being introduced into the MPRB groundwater via an unknown source. Further studies could be done to identify the origin of Cl contamination in this region.

4.2 Lower Passaic River Basin

The Lower Passaic River Basin is a densely populated urban and industrial area. In such areas, anthropologic effluence results in substantial contamination of soil and groundwater. In this study, the pollution of the LPRB groundwater by deicing salts is clearly observed through geostatistical analysis. In the time series, deicing ion concentrations for Cl, Na, Ca, as well as TDS averages showed sharp increasing trends throughout time, while the domestic Mg ions did not. These trends indicate that the domestic ions Ca and Mg are increasing at different rates, suggesting that Ca is being introduced into the groundwater from an outside source such as calcium chloride. Prediction interval analyses showed that Cl and Na increased from the 1960s to the 2000s at statistically unpredicted rates, signifying the application of sodium chloride. Bivariate analyses indicated strong correlations between deicing salts Na and Cl ($r^2 = 0.78$, $n = 76$) and moderate correlations between Cl and Ca ($r^2 = 0.62$, $n = 76$), but very weak correlation between Na and Ca ($r^2 = 0.23$, $n = 76$). The results of the bivariate analyses suggest that there is an observable relationship between ions of the same deicing material, but that there is no intermolecular relationship between Na of sodium chloride and Ca of calcium chloride.

The large expanses of shale and sandstone underlaying the LPRB had some influence on Ca ion concentrations in the region’s groundwater. Since Ca is supplied into the groundwater domestically, there are two known sources for the ion: bedrock weathering and anthropogenic calcium chloride application. The fact that Ca has two sources could have resulted in a reduction of the Cl and Ca correlation during bivariate analysis. However, bedrock weathering should transpire steadily throughout a lengthy timeframe (hundreds of thousands to millions of years) much longer than the 50-year study period of this research. Consequently, bedrock weathering can be considered an important but minor source of Ca ions into the LPRB.

Cl, Na, and Ca ion concentrations are found to increase at rates related to the total mass application of road salt and brine (NaCl) and liquid calcium chloride ($CaCl_2$). Cl shows the largest concentration increase, as it has a total atomic percentage of 60 between both deicing salts together, therefore making it the most abundant ion. Na shows the second largest increase as it has an atomic ratio of 1:1 in road salt, which is by far the most extensively implemented deicing salt. Ca shows the smallest increase as it has an atomic ratio of 1:2 in the least common deicing material, liquid $CaCl_2$. Future research could be done on measuring molar ion increases in comparison to their application amounts to deduce if the two are directly proportional.

5. Conclusion

The differences in groundwater ion composition between the Middle and Lower Passaic River Basin are apparent. In the LPRB, the exponential ion concentration increases for Na, Cl, and to a lesser amount, Ca, is indicative of the anthropogenic use of road salt, brine, and liquid calcium chloride for road deicing in the winter seasons. The fact that the increases for these same ions are pronounced to a much lesser extent in the MPRB is likely due to the combination of large water reservoirs diluting and leaching surface measurements, low-porosity bedrock preventing seepage of contaminants, and relatively lower amounts of road salt application in the region.

Overall, the results of this study indicate that the magnitude of contamination of Na, Cl, and Ca ions in regional groundwater is greatly influenced by the hydrology and geology of a specific region. As seen with the MPRB geostatistical and hydrochemical analyses, regions with igneous and metamorphic bedrock are less likely to absorb pollutants, and large volumes of surface water leach and dilute shallow, upper layers of earth. The LPRB analyses indicated that regions with sedimentary rock are more likely to absorb contaminants for longer periods of time, and surface water volumes result in less percolation. Additionally, the rate of road salt application due to road density also plays a major role in the contamination of the region. Areas with high road density such as the LPRB have a greater risk of contamination than areas with low road densities such as the MPRB. However, since the two study areas are diametrically opposed, containing the complete opposite traits in hydrology, geology, and road density, it is difficult to determine which of these three factors has the largest bearing on groundwater contamination. Whether the MPRB results were influenced to a greater degree by the large surface water supply, low-porosity bedrock, or lack of roads and vice versa for the LPRB has not been determined. Nevertheless, this study ascertains that hydrology, geology, and road densities are the three major contributors to the variances in groundwater composition and contamination between the MPRB and the LPRB.

With the findings of this research, regions of high, medium, and low contamination concern may be categorized based on their hydrology, geology, and road density classifications. It can be inferred that areas identical to the LPRB, with low surface water volume, porous bedrock, and an extensive road network, are likely to be affected by anthropogenic contamination through road deicing. Identification of problematic regions such as the LPRB can be utilized by winter maintenance management agencies to help determine whether alternate deicing methods should be practiced in these areas. Identification of low problematic areas such as the MPRB is useful in minimizing time and monetary burden on the agency and increasing efficiency of mineral and material allocation. It is recommended that further research be conducted focusing on the roles that surface water volume, bedrock porosity and weathering, and deicing application rates play in determining groundwater contamination rates.

Literature Cited

Alley, W. M. (1993). *Regional ground-water quality*. New York: Van Nostrand Reinhold.

Anderson, G. (1986). Silica, diatoms and a freshwater productivity maximum in Atlantic Coastal Plain estuaries, Chesapeake Bay. *Estuarine, Coastal And Shelf Science*, *22*(2), 183-197. doi: 10.1016/0272-7714(86)90112-5

Boyte, S., Wylie, B., Howard, D., Dahal, D., & Gilmanov, T. (2017). Estimating carbon and showing impacts of drought using satellite data in regression-tree models. *International Journal Of Remote Sensing*, *39*(2), 374-398. doi: 10.1080/01431161.2017.1384592

Chebotarev I. (1955) Metamorphism of Natural Waters in the Crust of Weathering. Geochimica et Cosmochimica Acta, 8, 137-170

Degrees of freedom. (1998). *Engineering Science & Education Journal*, *7*(5), 194-195. doi: 10.1049/esej:19980501

Dixon, W.J. (Editor), 1975. BMDP Biomedical Computer Programs. University of California, Los Angeles, California, pp. 593-621.

Federal Highway Administration. 1989 Highway Statistic 1988. U.S. Department of Transportation.

Fetter, C. W. *Applied Hydrogeology*. 4th ed., Pearson Education Limited, 2014.

Foos, A. (2003). Spatial distribution of road salt contamination of natural springs and seeps, Cuyahoga Falls, Ohio, USA. *Environmental Geology*, *44*(1), 14-19. doi: 10.1007/s00254-002-0724-7

Freeze, R., & Cherry, J. (1979). *Groundwater*. Englewood Cliffs, N.J: Prentice-Hall.

Godwin, K., Hafner, S., & Buff, M. (2003). Long-term trends in sodium and chloride in the Mohawk River, New York: the effect of fifty years of road-salt application. *Environmental Pollution*, *124*(2), 273-281. doi: 10.1016/s0269-7491(02)00481-5

Granato, G., & Jones, S. (2014). Stochastic Empirical Loading and Dilution Model for Analysis of Flows, Concentrations, and Loads of Highway Runoff Constituents. *Transportation Research Record: Journal Of The Transportation Research Board*, *2436*(1), 139-147. doi: 10.3141/2436-14

Hocking, D., Thorson, J., O'Neil, K., & Letcher, B. (2018). A geostatistical state-space model of animal densities for stream networks. *Ecological Applications*, *28*(7), 1782-1796. doi: 10.1002/eap.1767

Howard, K. W., & Haynes, J. (1993). Groundwater contamination due to road de-icing chemicals—salt balance implications. *Geoscience Canada*, *20*(1).

Kuemmel, David, and Rashad Hanbali. 1992. Accident analysis of ice control operations. Marquette University Department of Civil, Construction and Environmental Engineering. Milwaukee, WI.

Naeser, C., Naeser, N., Newell, W., Southworth, S., Edwards, L., & Weems, R. (2016). Erosional and depositional history of the Atlantic passive margin as recorded in detrital zircon fission-track ages and lithic detritus in Atlantic Coastal plain sediments. *American Journal Of Science*, *316*(2), 110-168. doi: 10.2475/02.2016.02

New Jersey Bureau of GIS. (2018). Retrieved from https://www.state.nj.us/dep/gis/stateshp.html

NJDEP-Watershed Restoration-Watershed Information. (2018). Retrieved from https://www.nj.gov/dep/watershedrestoration/info.html

NJDOT. (2018). Roadway Information and Traffic Monitoring System Program - Public Roadway Mileage & Vehicle Miles Traveled. Retrieved from https://www.state.nj.us/transportation/refdata/roadway/vmt.shtm

NJDOT. (2018). *Winter Readiness, Expenditures, About NJDOT*. [online] State.nj.us. Available at: https://www.state.nj.us/transportation/about/winter/expenditures.shtm [Accessed 1 Nov. 2018].

Olsen, P. (1980). *The latest Triassic and Early Jurassic formations of the Newark Basin, eastern North America, Newark Supergroup*. New Brunswick, N.J.: New Jersey Academy of Science.

Peters, N., & Turk, J. (1981). INCREASES IN SODIUM AND CHLORIDE IN THE MOHAWK RIVER, NEW YORK, FROM THE 1950'S TO THE 1970'S ATTRIBUTED TO ROAD SALT. *Journal Of The American Water Resources Association*, *17*(4)

Ries, Henrich, 1901. Lime and Cement Industries of New York. New York State Museum Bulletin 44(8):968 pp.

Riva-Murray, K., Riemann, R., Murdoch, P., Fischer, J., & Brightbill, R. (2010). Landscape characteristics affecting streams in urbanizing regions of the Delaware River Basin (New Jersey, New York, and Pennsylvania, U.S.). *Landscape Ecology*, *25*(10), 1489-1503. doi: 10.1007/s10980-010-9513-y

Salt Institute. (2018). Safe Winter Roads Protect Lives - Salt Institute. Retrieved from http://saltinstitute.org/research/safe-winter-roads-protect-lives/

Snedecor, G.W., 1946. Statistical Methods. Iowa State College Press, Ames, Iowa, pp. 118-121

Stets, E., Lee, C., Lytle, D., & Schock, M. (2018). Increasing chloride in rivers of the conterminous U.S. and linkages to potential corrosivity and lead action level exceedances in drinking water. *Science Of The Total Environment*, *613-614*, 1498-1509. doi: 10.1016/j.scitotenv.2017.07.119

Transportation Research Board. 1974. NCHRP Synthesis of Highway Practice 24: Minimizing Deicing Chemical Use. National Research Council, Washington, D.C.

U.S. Geological Survey, 2014, Salt statistics, *in* Kelly, T.D., and Matos, G.R., comps., Historical statistics for mineral and material commodities in the United States: U.S. Geological Survey Data Series 140, accessed (2018), at http://minerals.usgs.gov/minerals/pubs/historical-statistics/.

USGS Nevada Excel for Hydrology. (2018). Retrieved from https://nevada.usgs.gov/tech/excelforhydrology/

Vecchioli, J., & Miller, E. *Water resources of the New Jersey part of the Ramapo River basin*. 1974. Retrieved from: https://pubs.er.usgs.gov/publication/wsp1974 [Accessed 3 Dec. 2018].

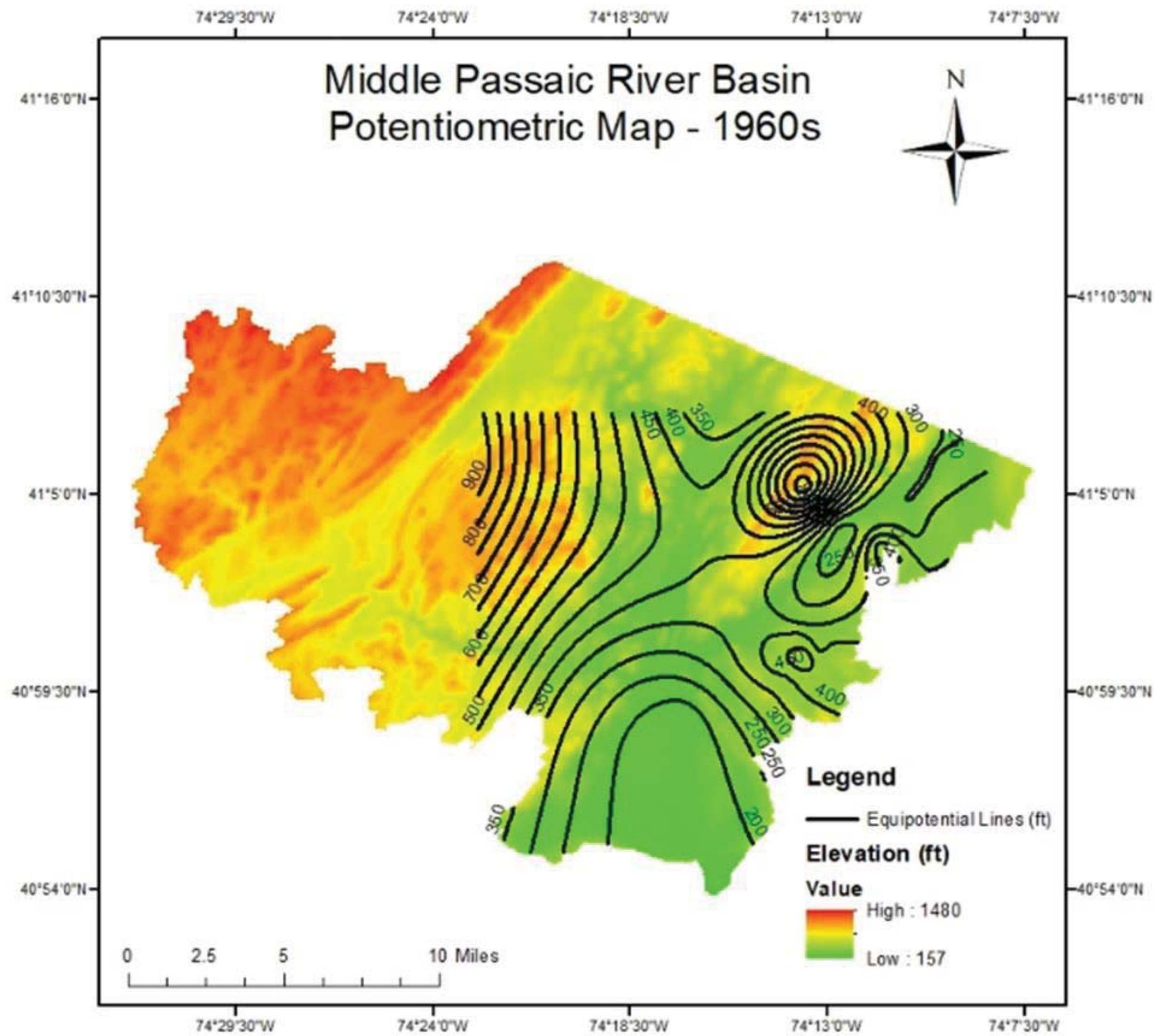

Figure 19a. Middle Passaic River Basin hydraulic head potentiometric maps for the 1960s.

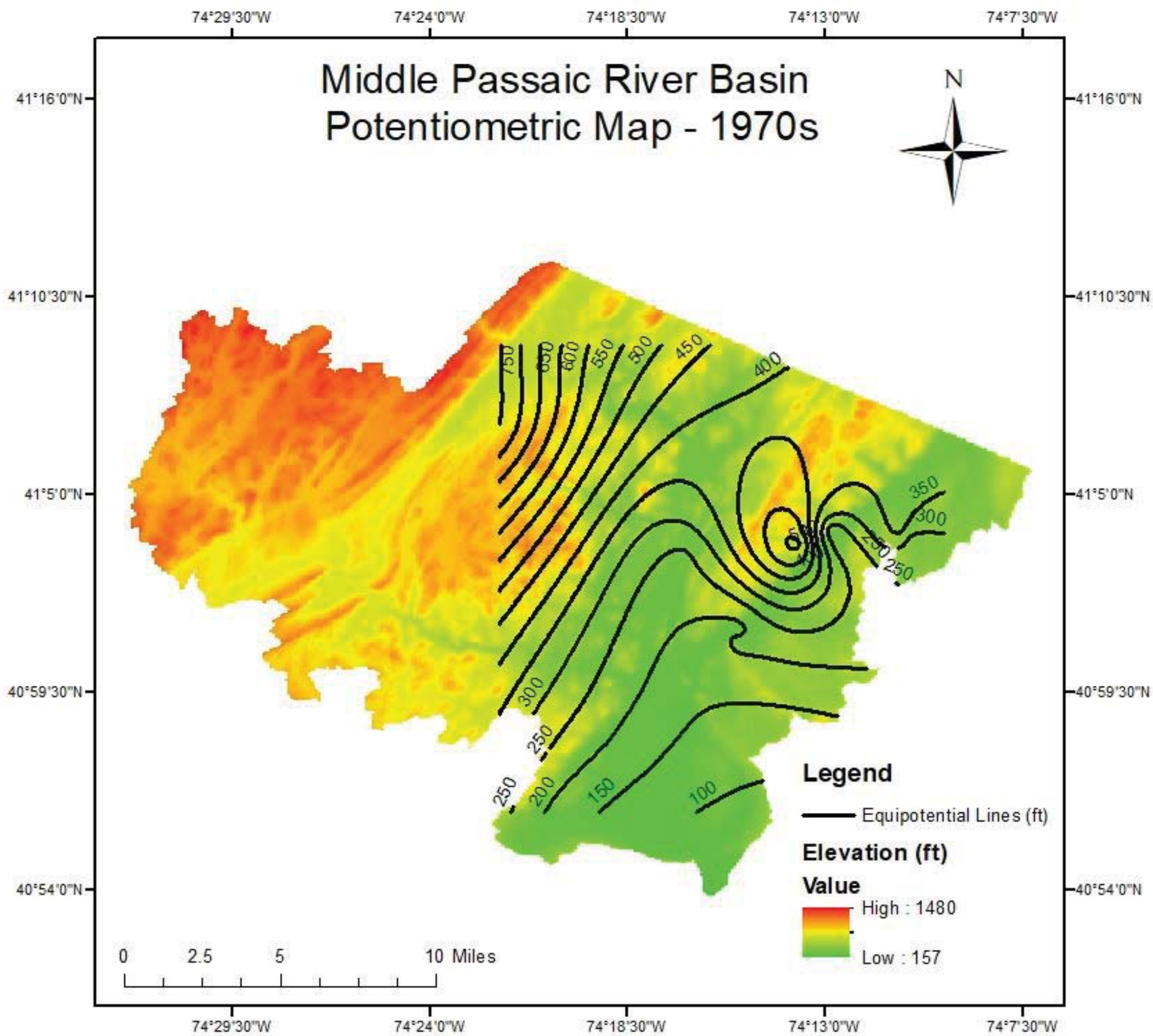

Figure 19b. Middle Passaic River Basin hydraulic head potentiometric maps for the 1970s.

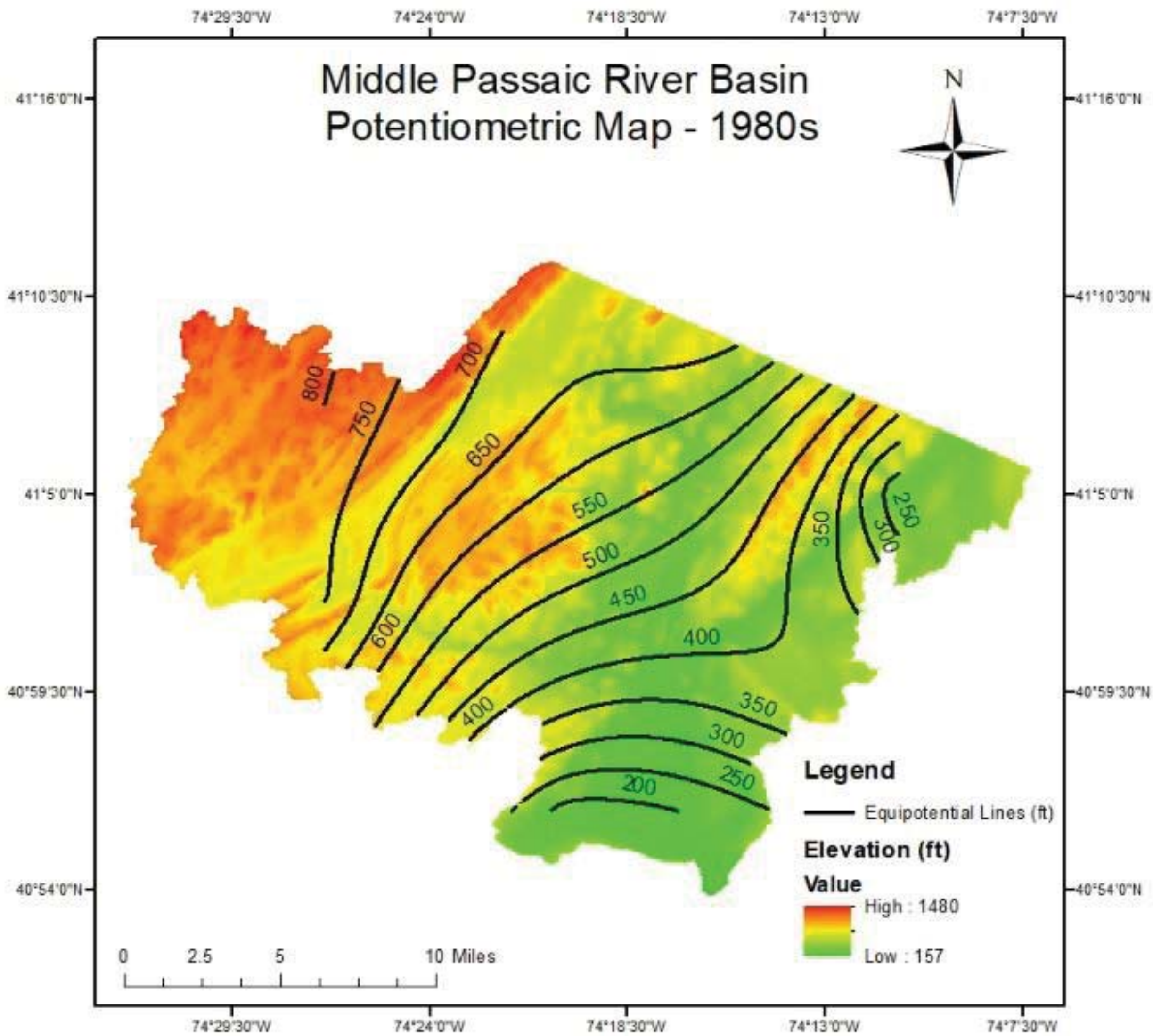

Figure 19c. Middle Passaic River Basin hydraulic head potentiometric map for the 1980s.

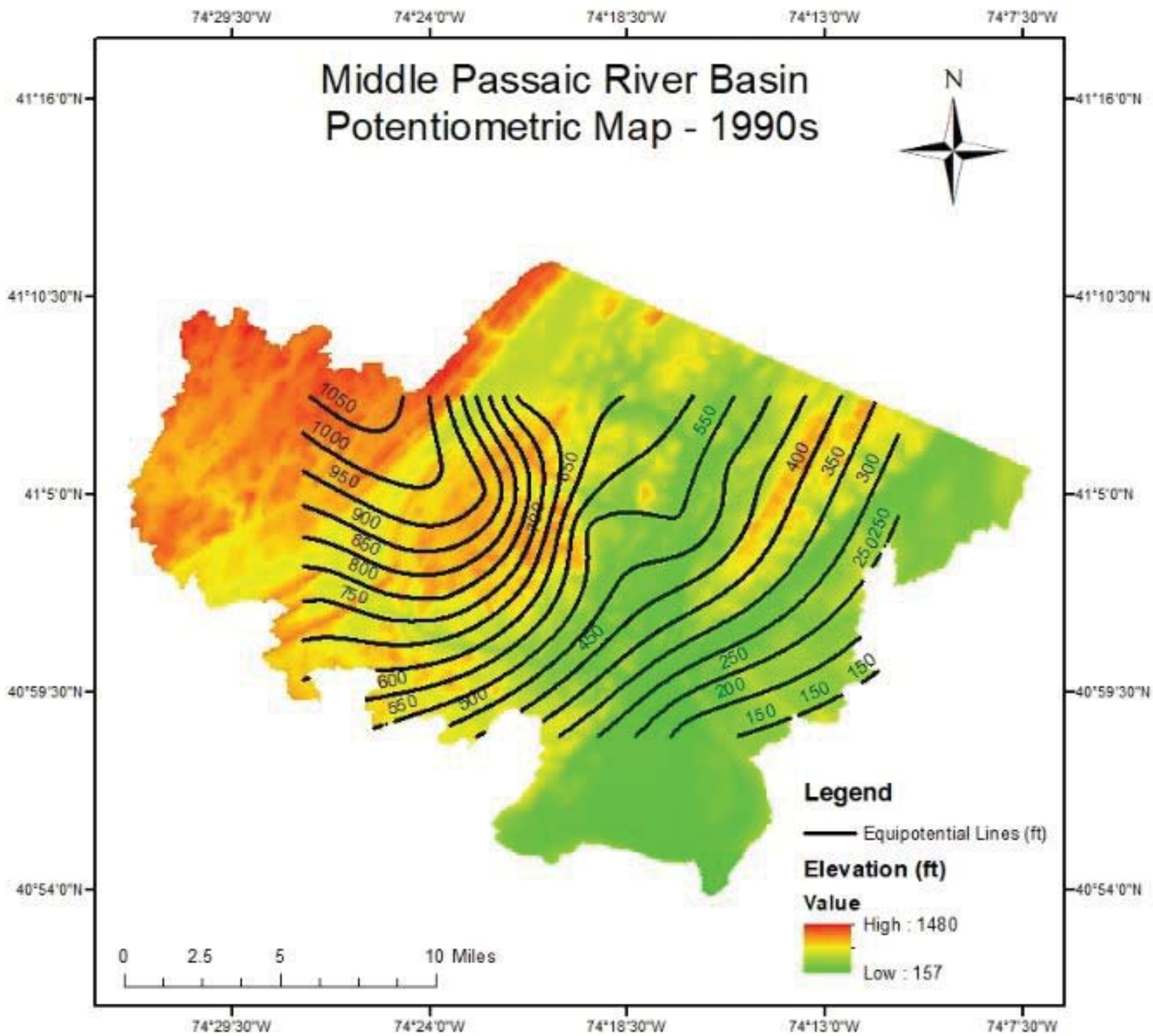

Figure 19d. Middle Passaic River Basin hydraulic head potentiometric map for the 1990s.

Legend

- ▲ Well Sites
- Ion Concentration Contour in mg/L

MPRB Geology

Rock Classification

- Albite-Oligoclase Granite
- Amphibolite
- Basalt-clast Conglomerate
- Bellvale Sandstone
- Berkshire Valley and Poxono Island Formations undivided
- Biotite-Quartz-Feldspar Gneiss
- Biotite-Quartz-Oligoclase Gneiss
- Boonton Formation
- Bushkill Member
- Clinopyroxene-Quartz-Feldspar Gneiss
- Cornwall Shale
- Diorite
- Feltville Formation
- Feltville Formation Conglomerate and Sandstone facies
- Franklin Marble
- Green Pond Conglomerate
- Hardyston Quartzite
- Hook Mt. Basalt
- Hornblende Granite
- Hornblende Syenite
- Hornblende-Quartz-Feldspar Gneiss
- Hypersthere-Quartz-Oligoclase Gneiss
- Jurassic Diabase
- Kanouse and Esopus Formations and Connelly Conglomerate
- Longwood Shale
- Microcline Gneiss
- Microperthite Alaskite
- Orange Mountain Basalt
- Passaic Formation Quatzite-clast Conglomerate facies
- Potassic Feldspar Gneiss
- Preakness Basalt
- Pyroxene Alaskite
- Pyroxene Gneiss
- Pyroxene Granite
- Quartz-Oligoclase Gneiss
- Quartz-pebble Conglomerate
- Quartzite
- Skunnemunk Conglomerate
- Syenite Gneiss
- Towaco Formation

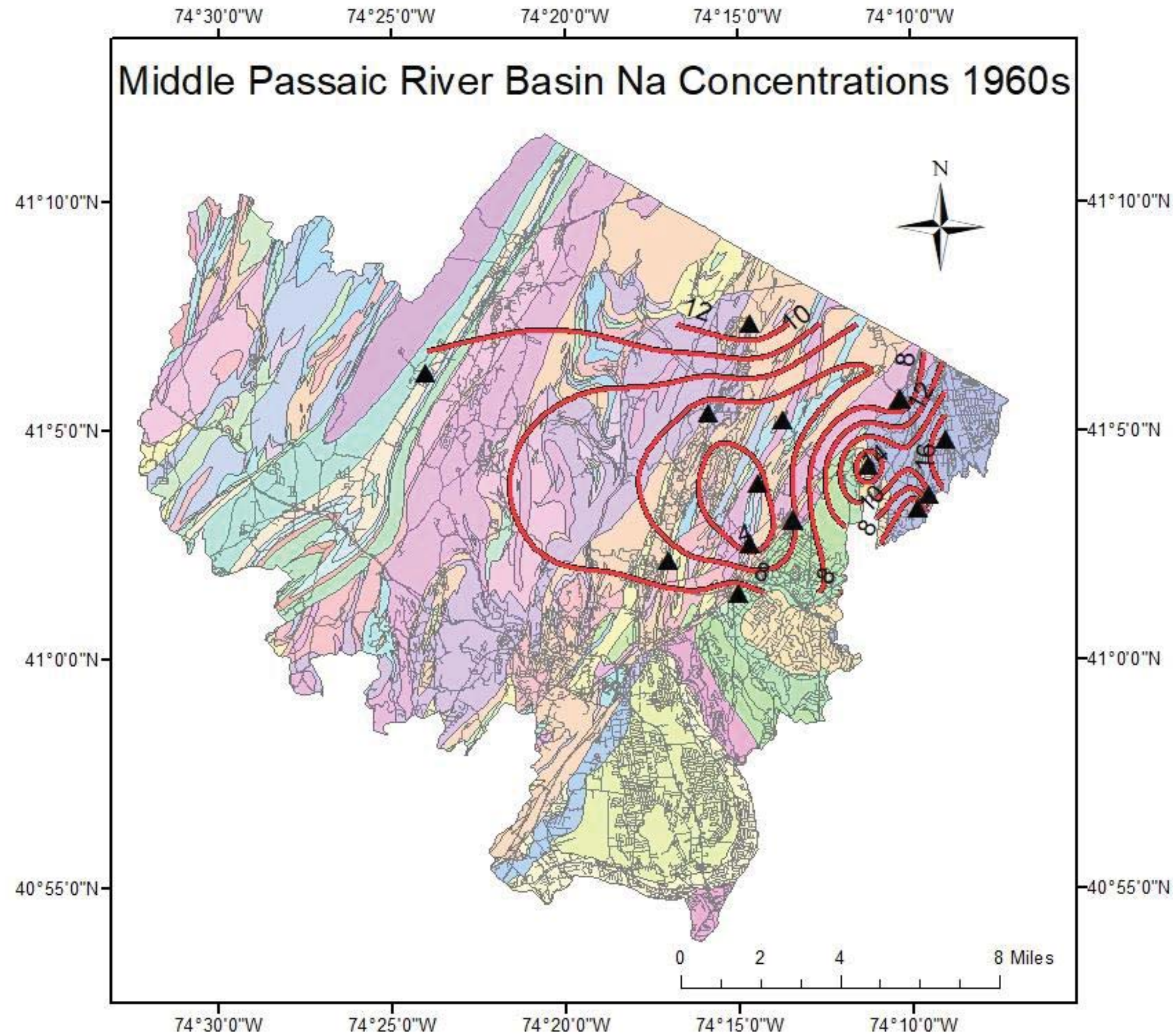

Figure 20a. Middle Passaic River Basin Na concentration contour map for the 1960s.

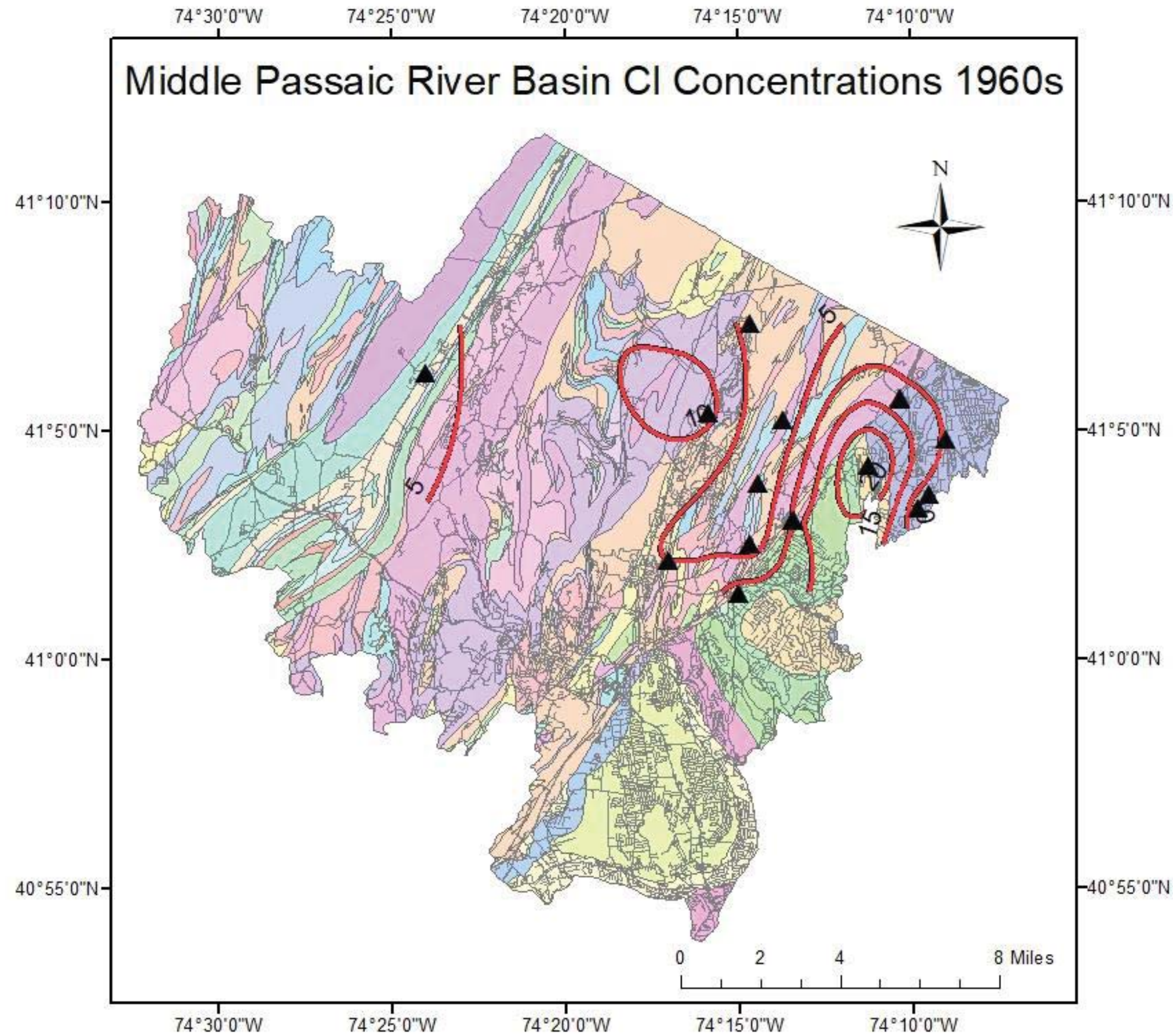

Figure 20b. Middle Passaic River Basin Cl concentration contour map for the 1960s.

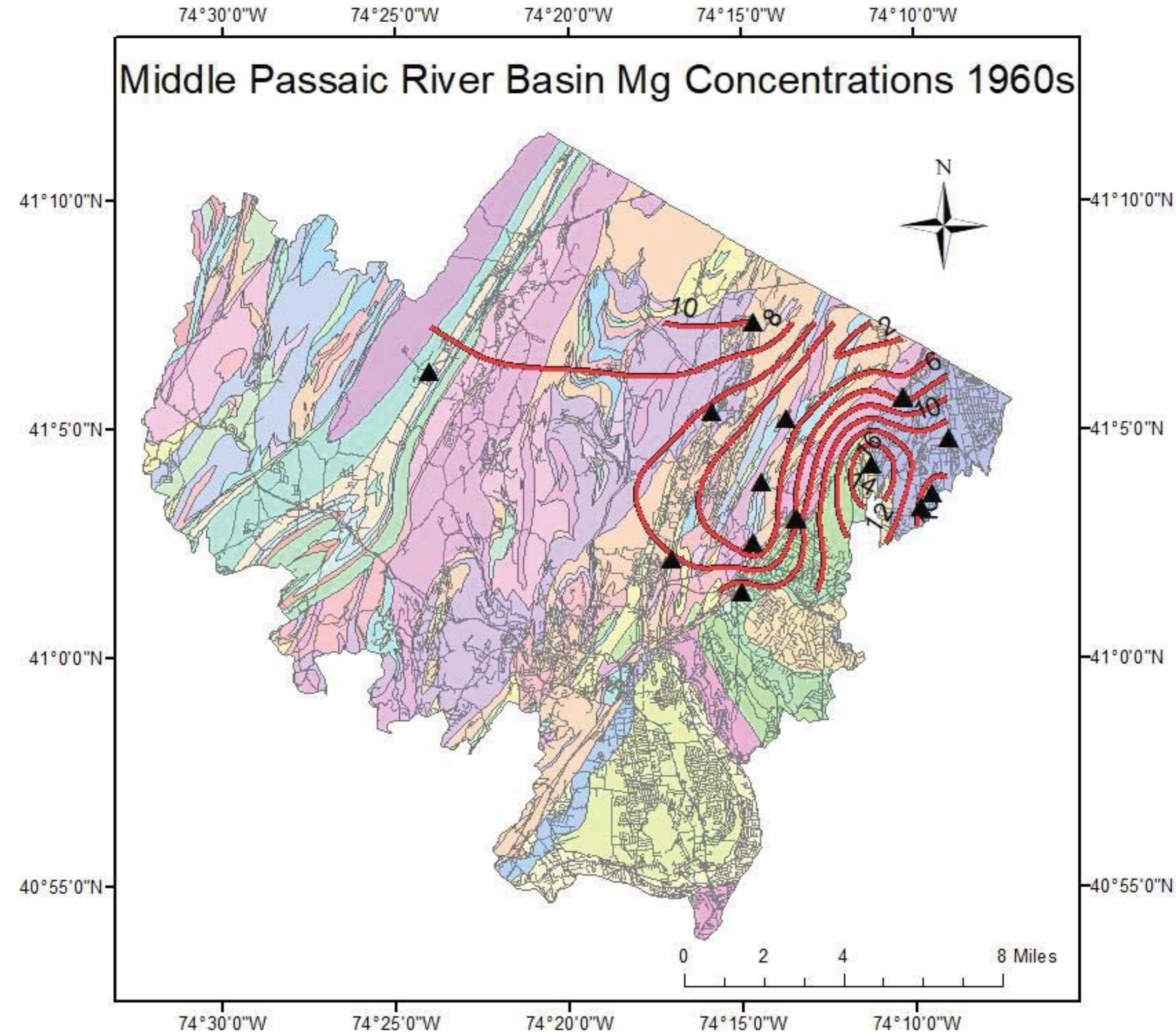

Figure 20c. Middle Passaic River Basin Mg concentration contour map for the1960s.

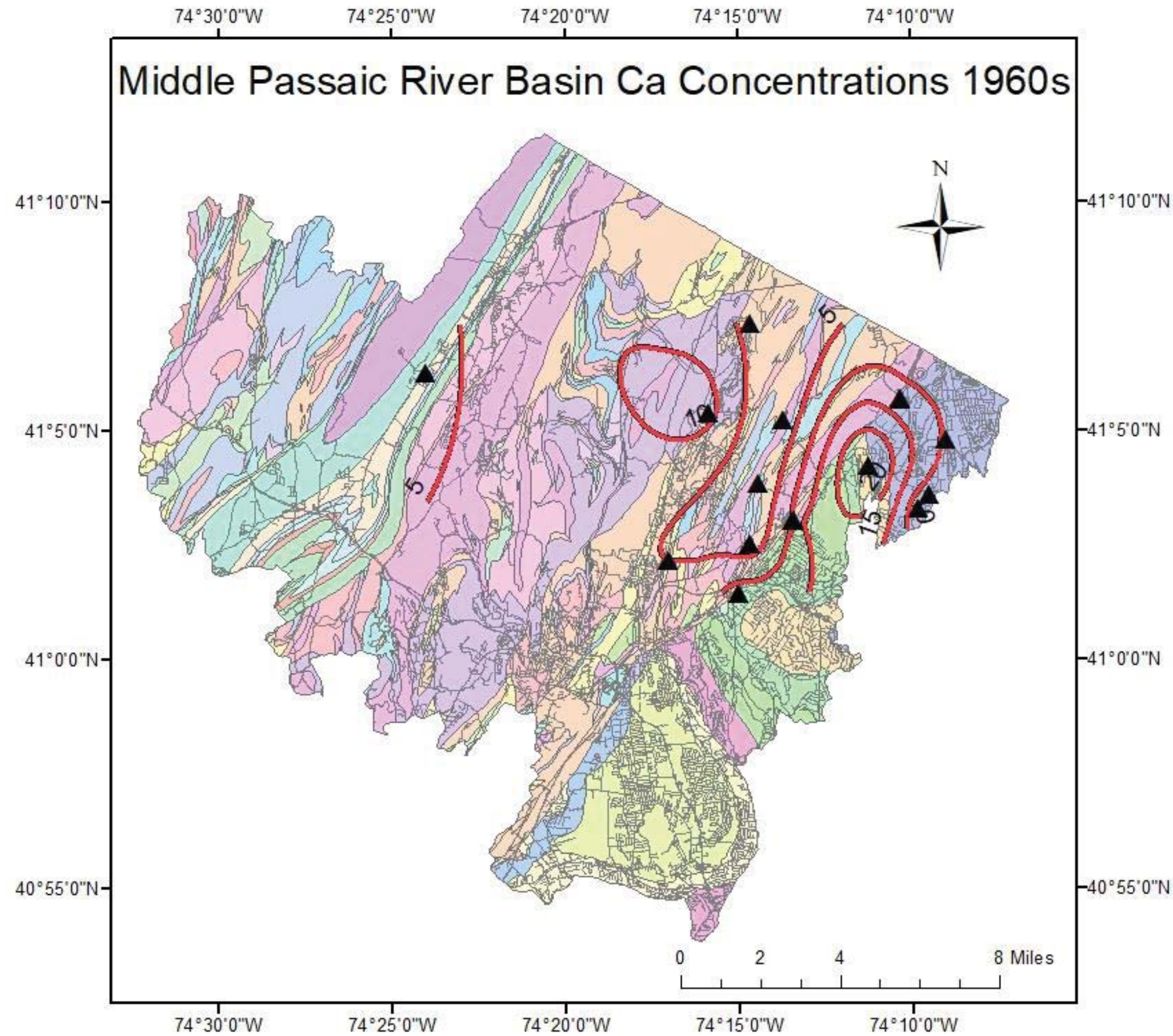

Figure 20d. Middle Passaic River Basin Ca concentration contour map for the 1960s.

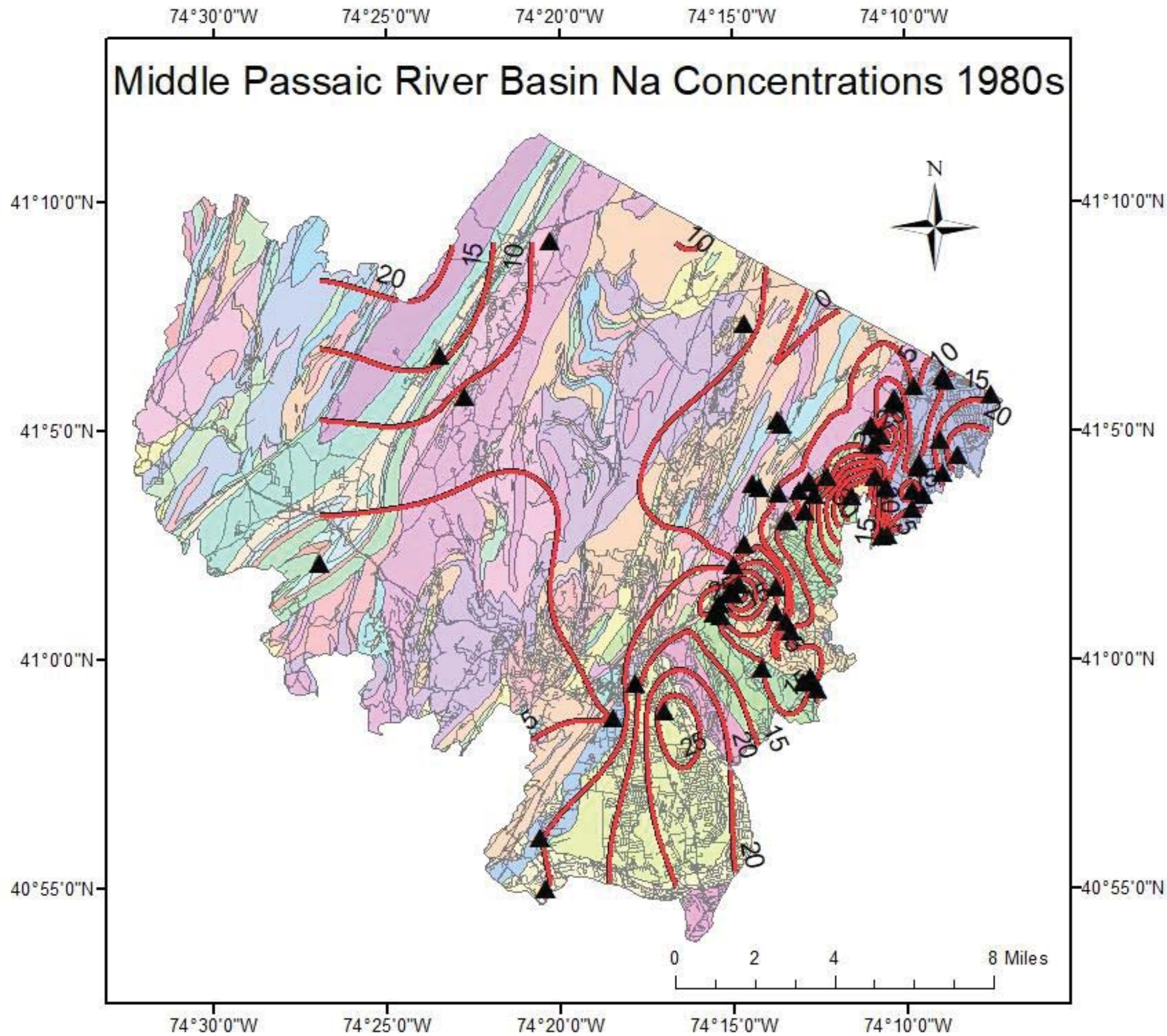

Figure 21a. Middle Passaic River Basin Na concentration contour map for the 1980s.

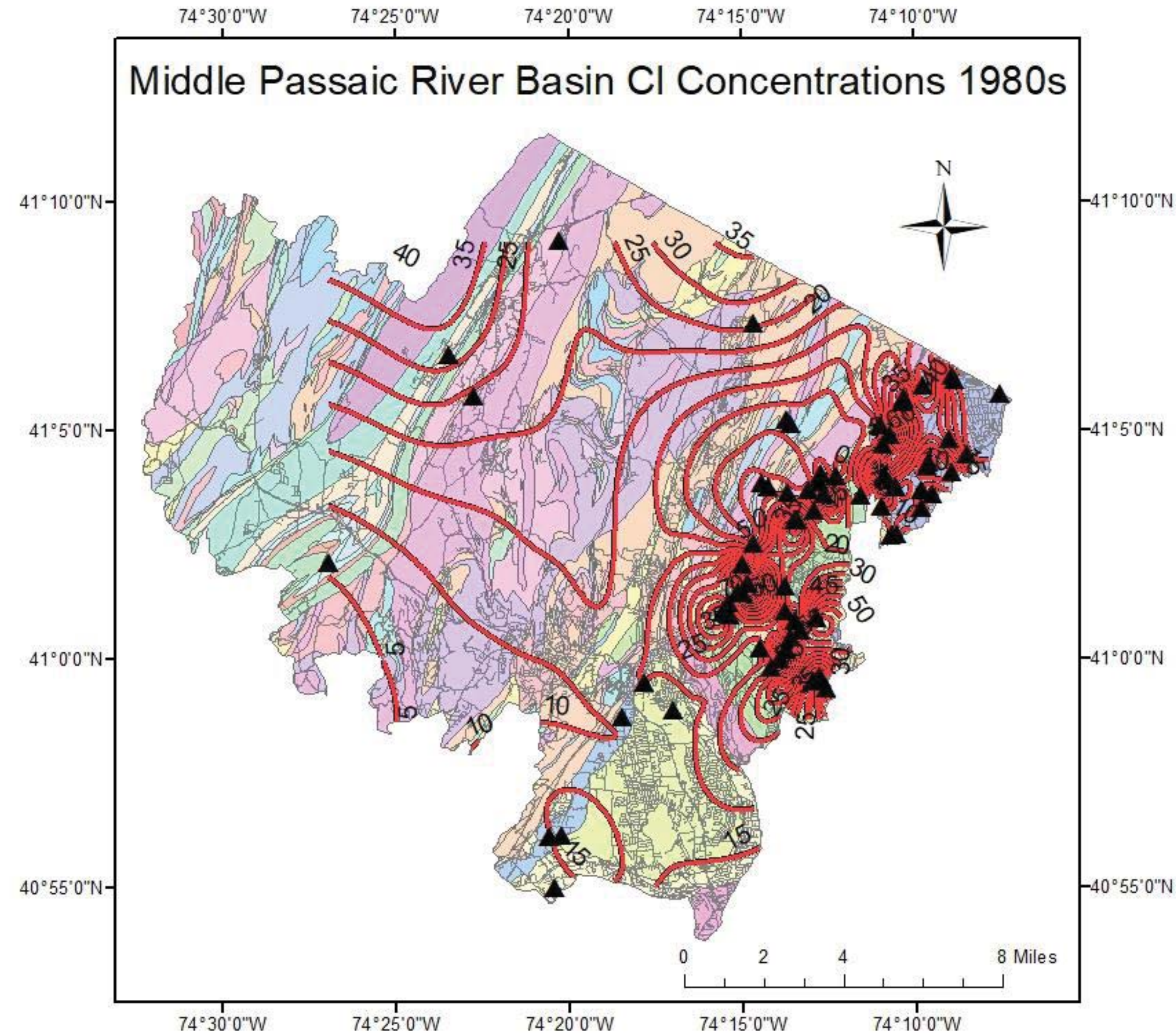

Figure 21b. Middle Passaic River Basin Cl concentration contour map for the 1980s.

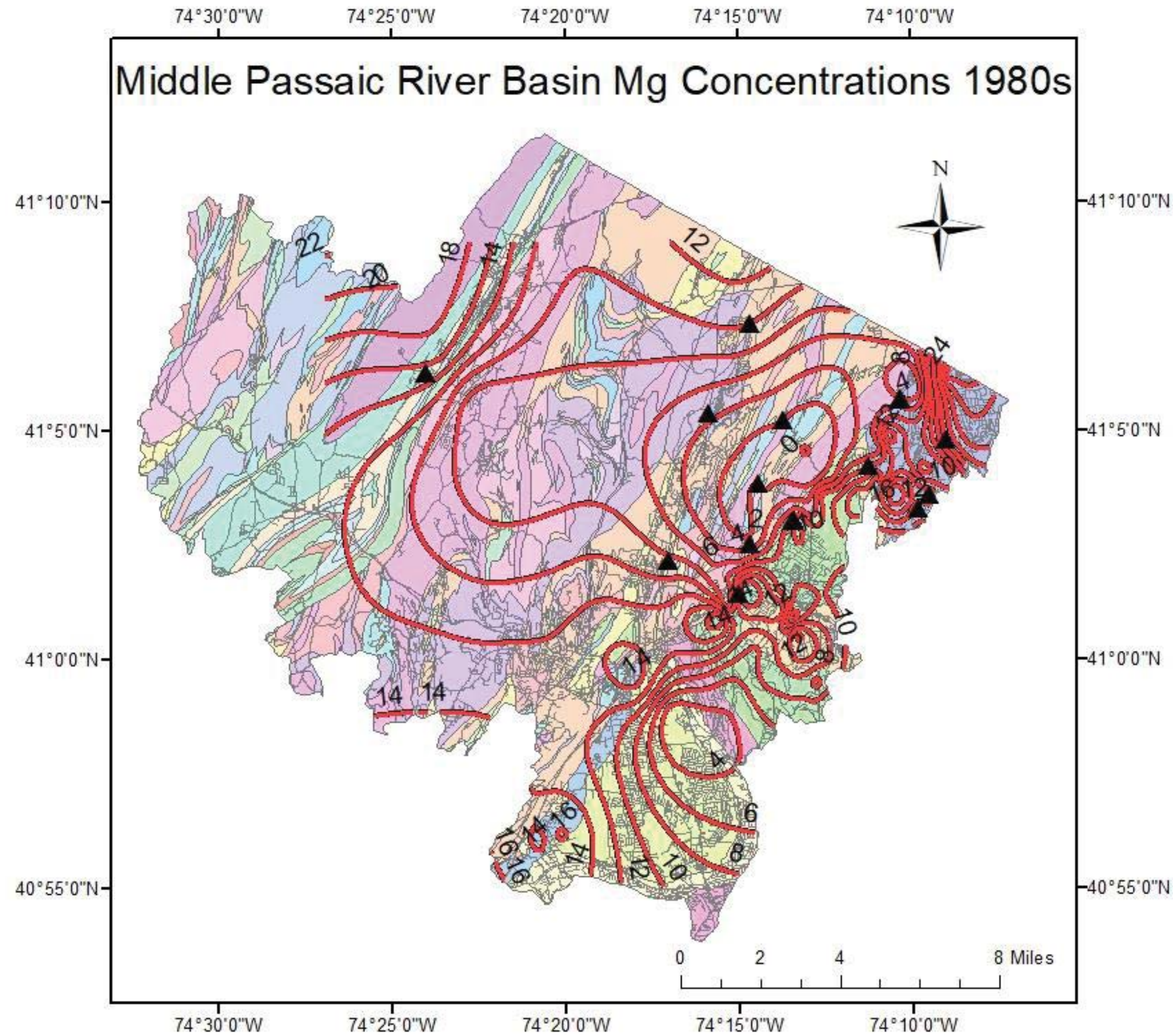

Figure 21c. Middle Passaic River Basin Mg concentration contour map for the 1980s.

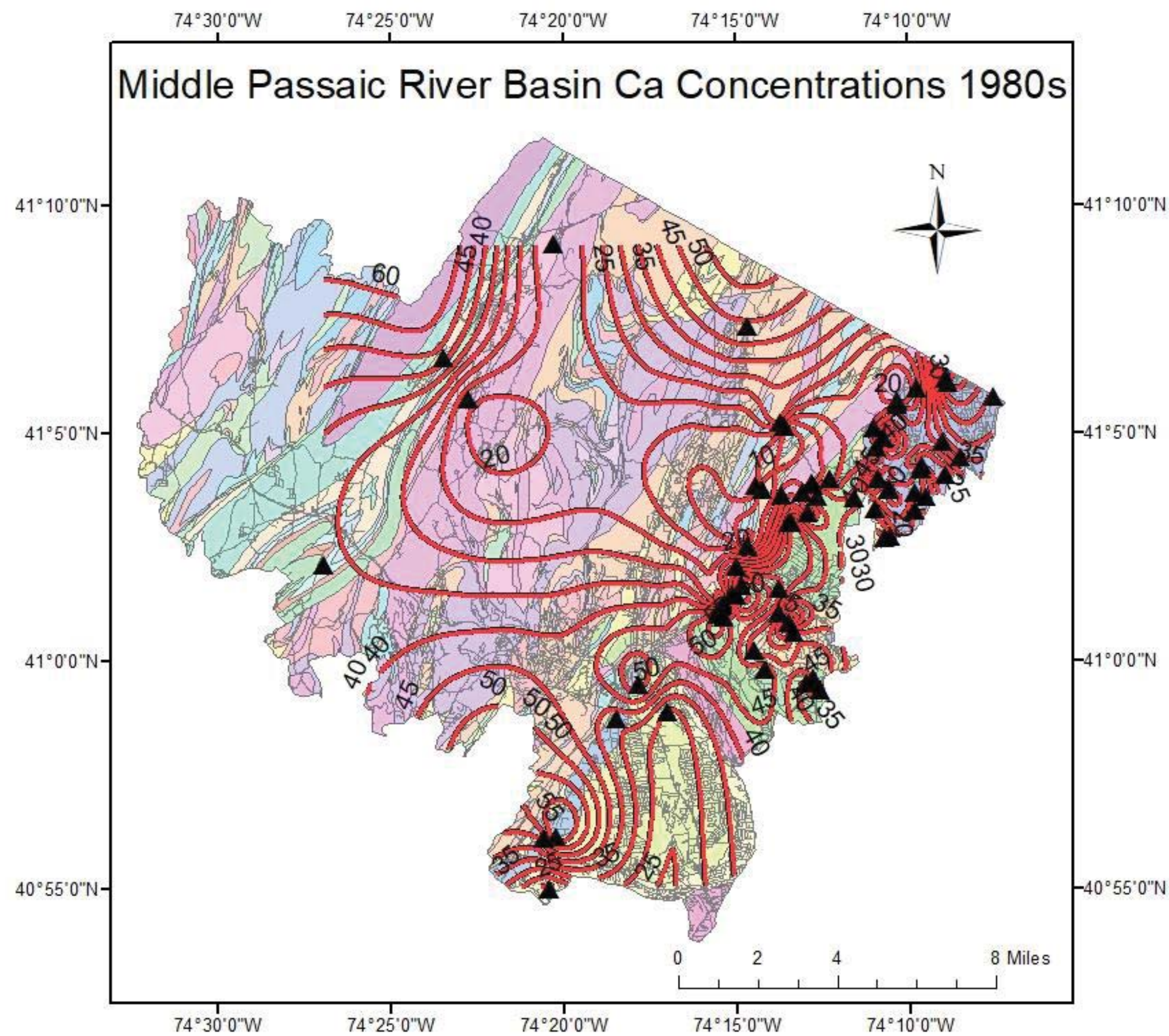

Figure 21d. Middle Passaic River Basin Ca concentration contour map for the 1980s.

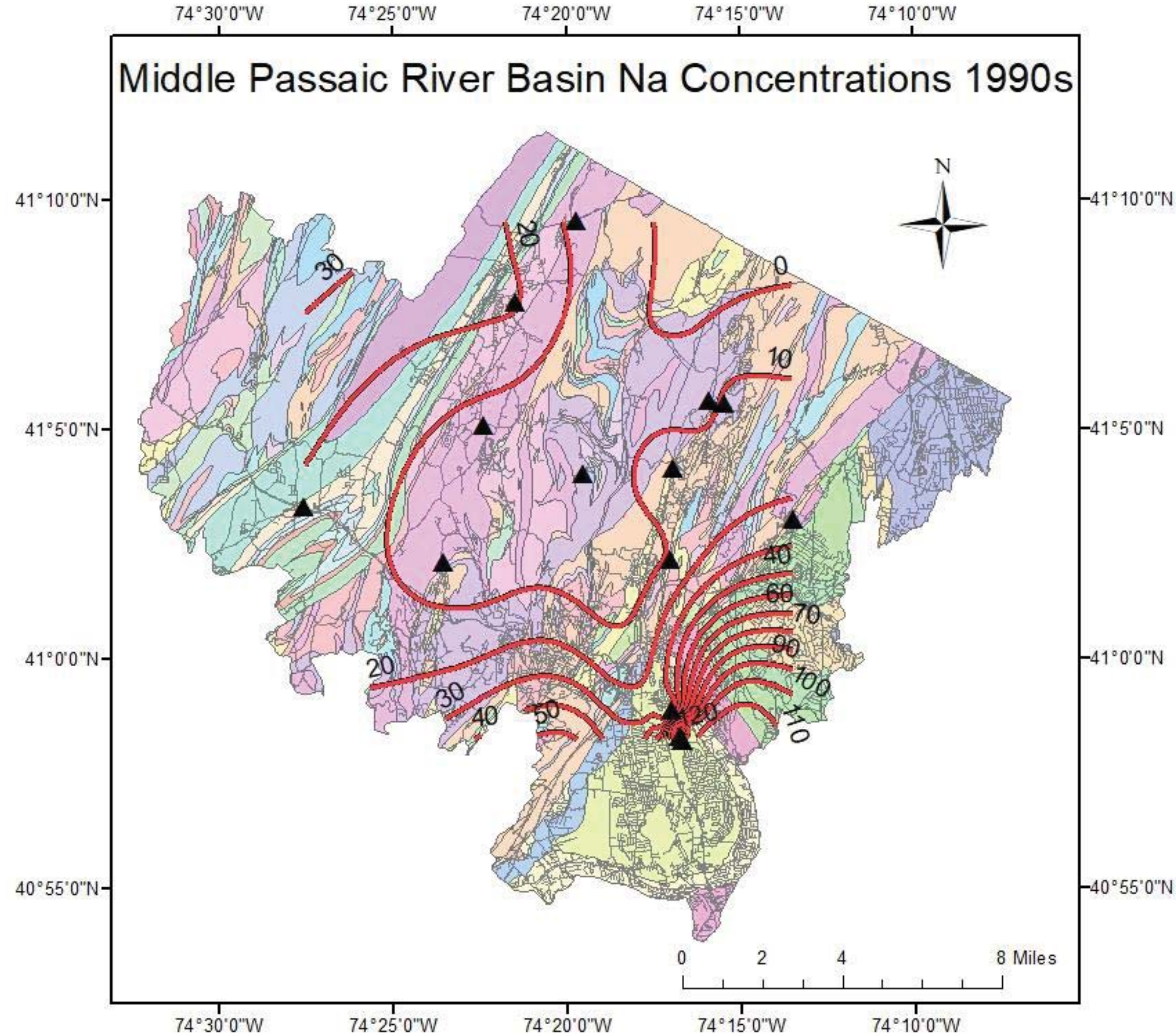

Figure 22a. Middle Passaic River Basin Na concentration contour map for the 1990s.

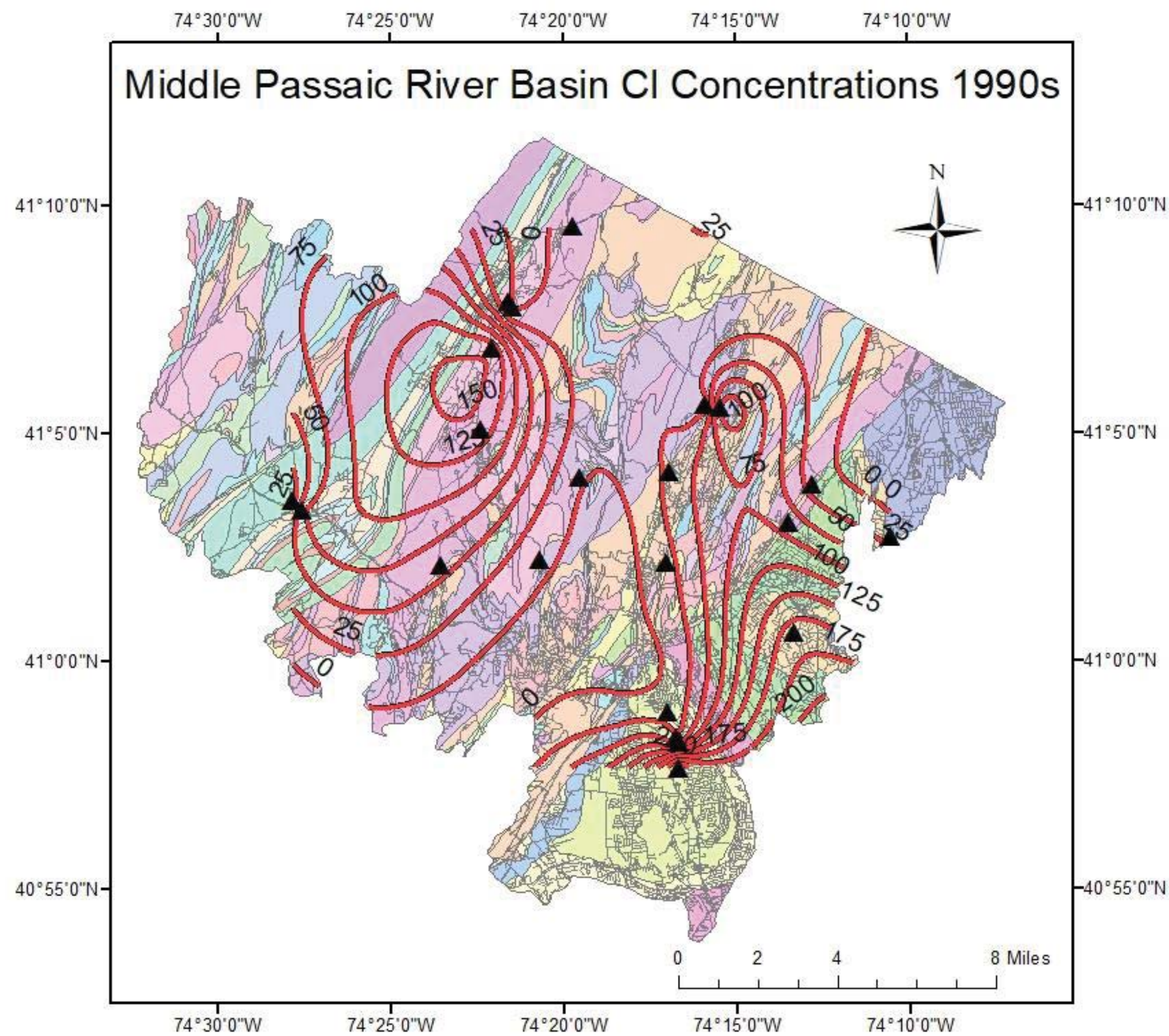

Figure 22b. Middle Passaic River Basin Cl concentration contour map for the1990s.

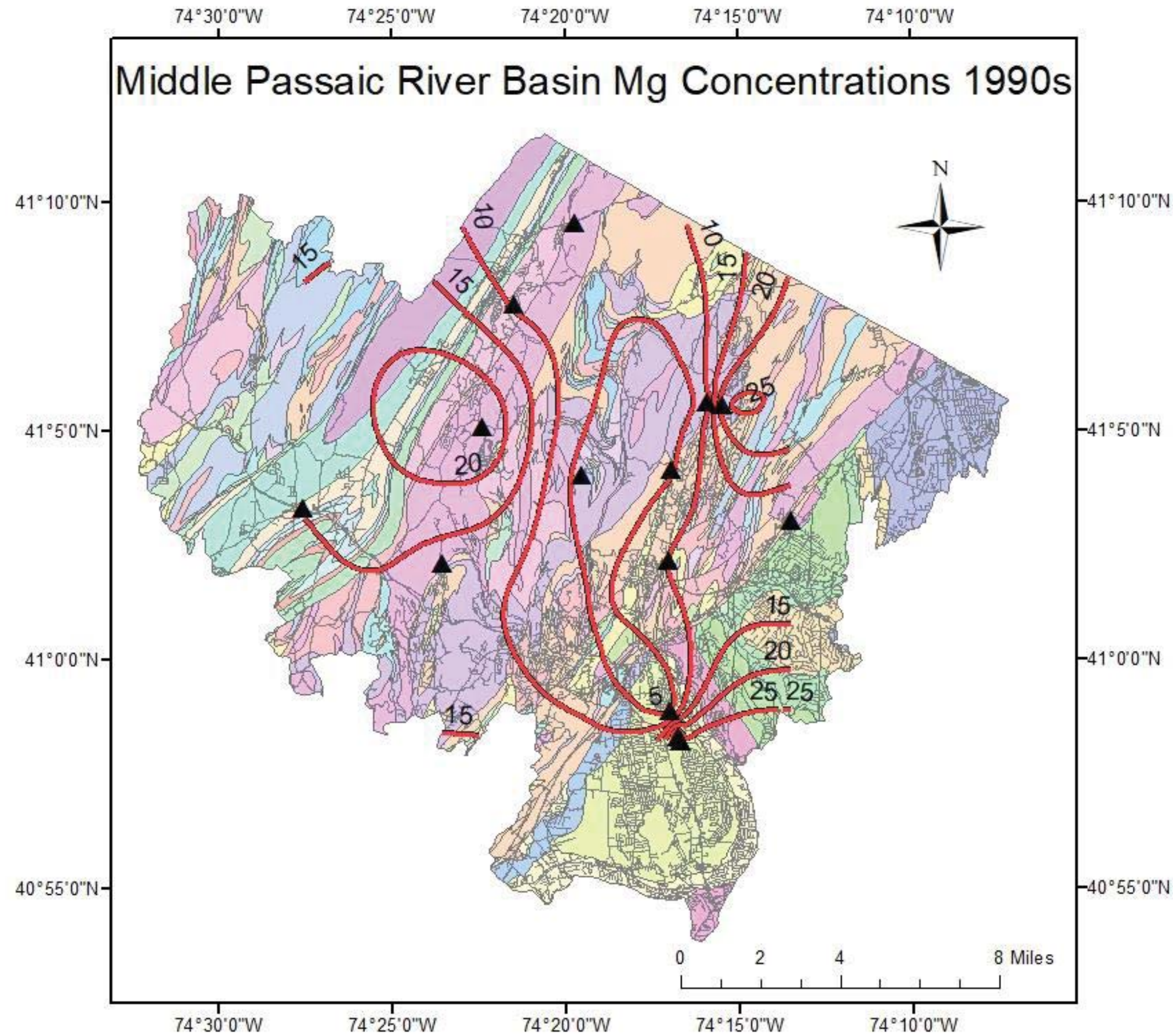

Figure 22c. Middle Passaic River Basin Mg concentration contour map for the 1990s.

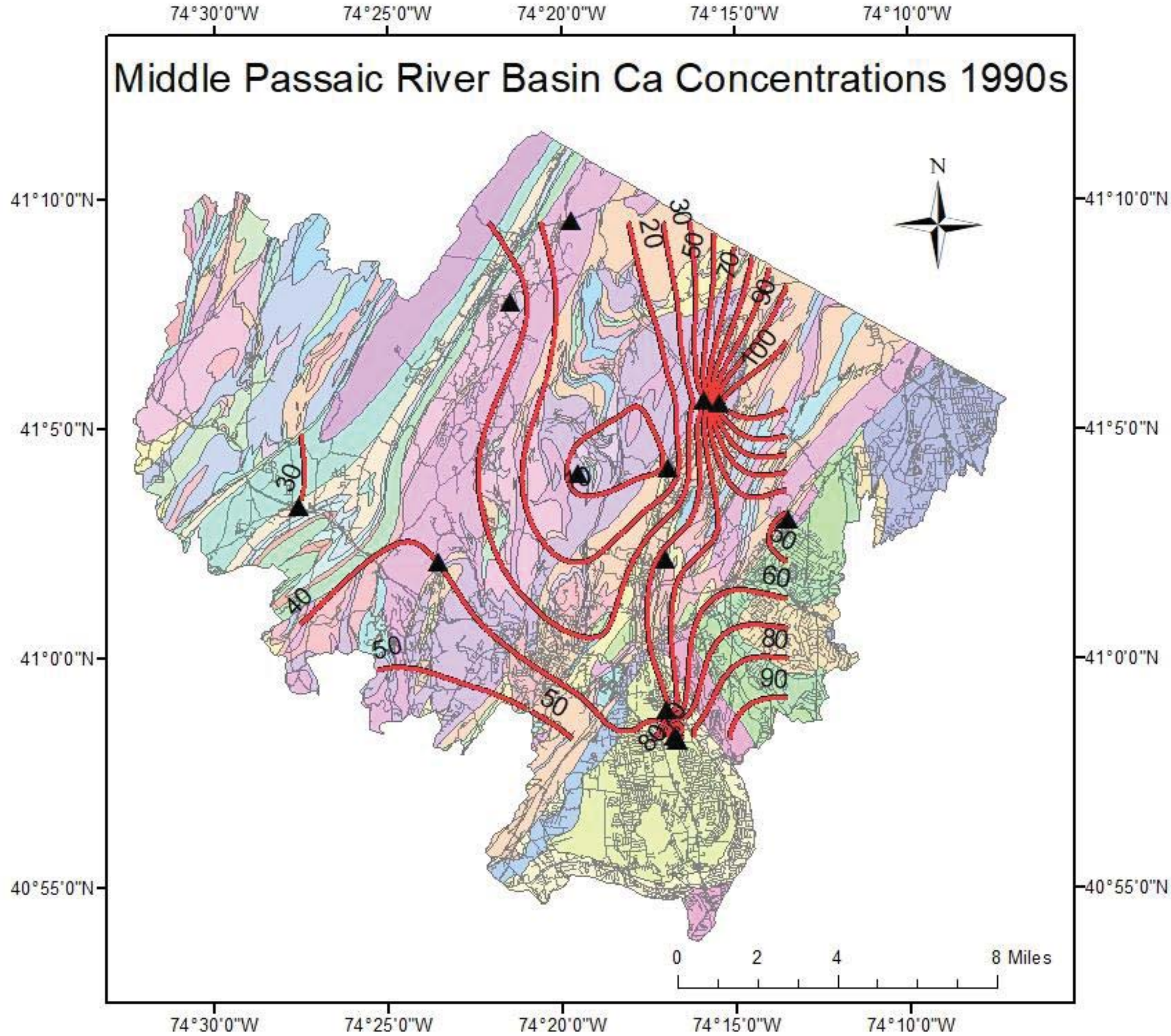

Figure 22d. Middle Passaic River Basin Ca concentration contour map for the 1990s.

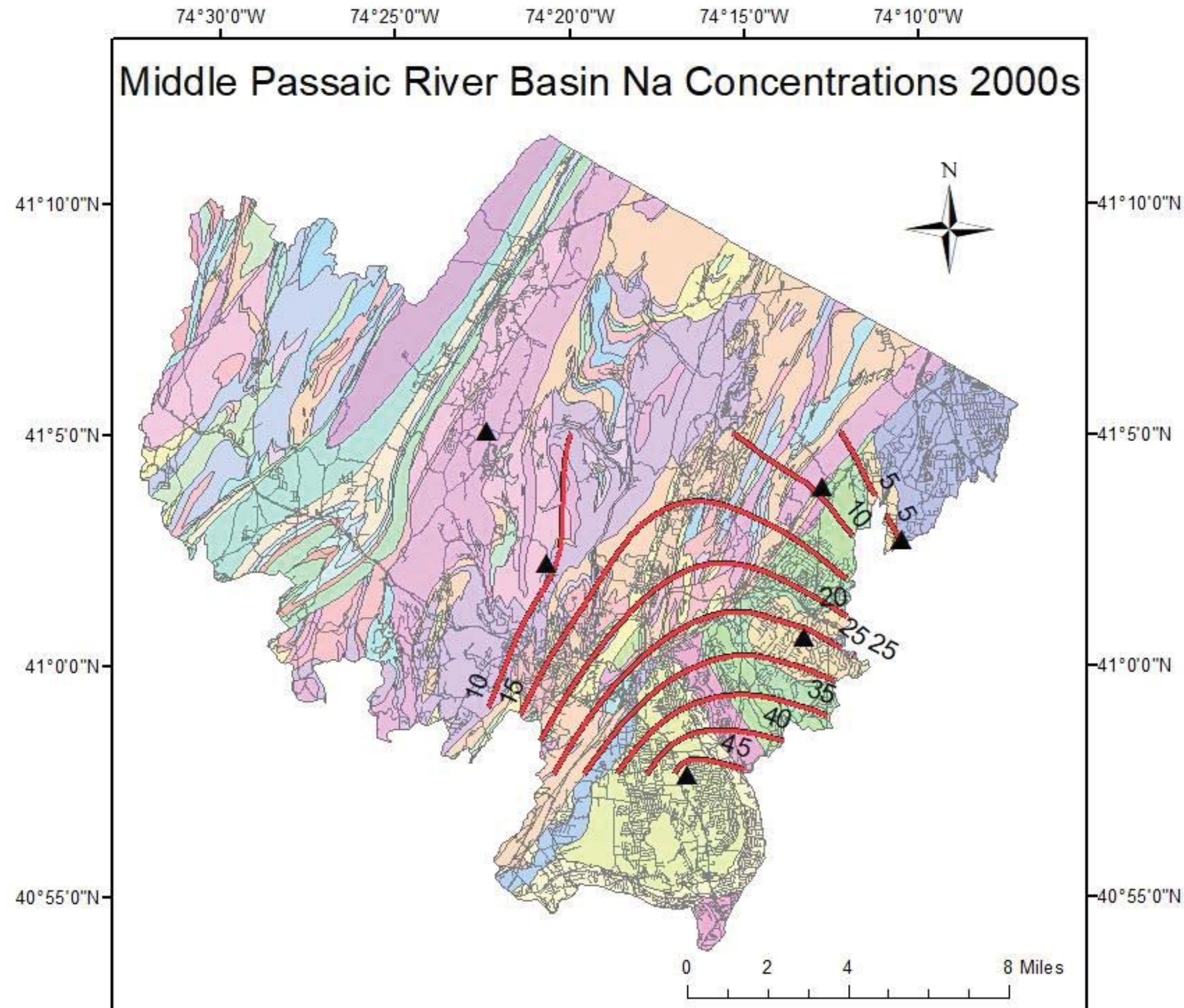

Figure 23a. Middle Passaic River Basin Na concentration contour map for 2000s.

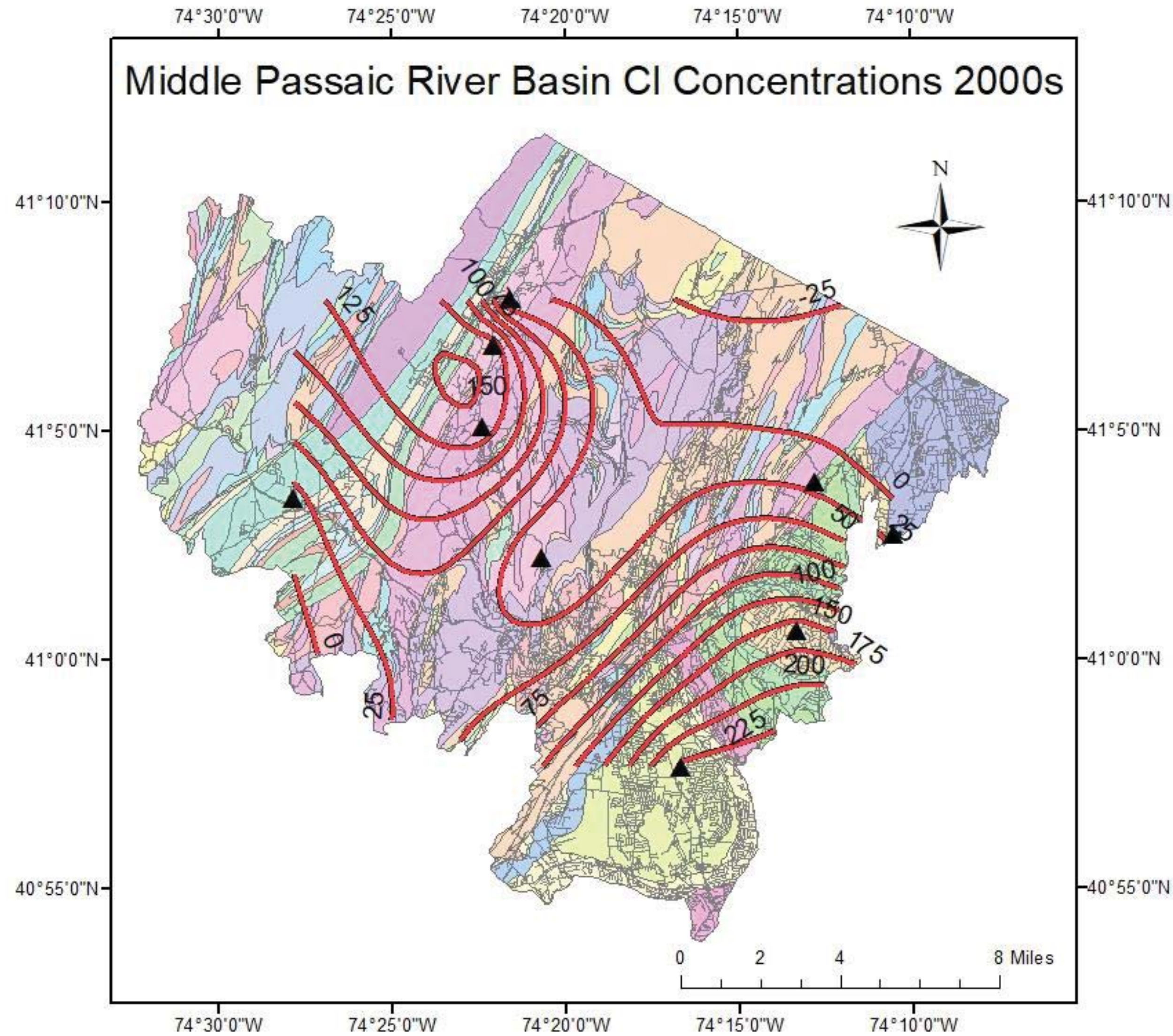

Figure 23b. Middle Passaic River Basin Cl concentration contour map for the 2000s.

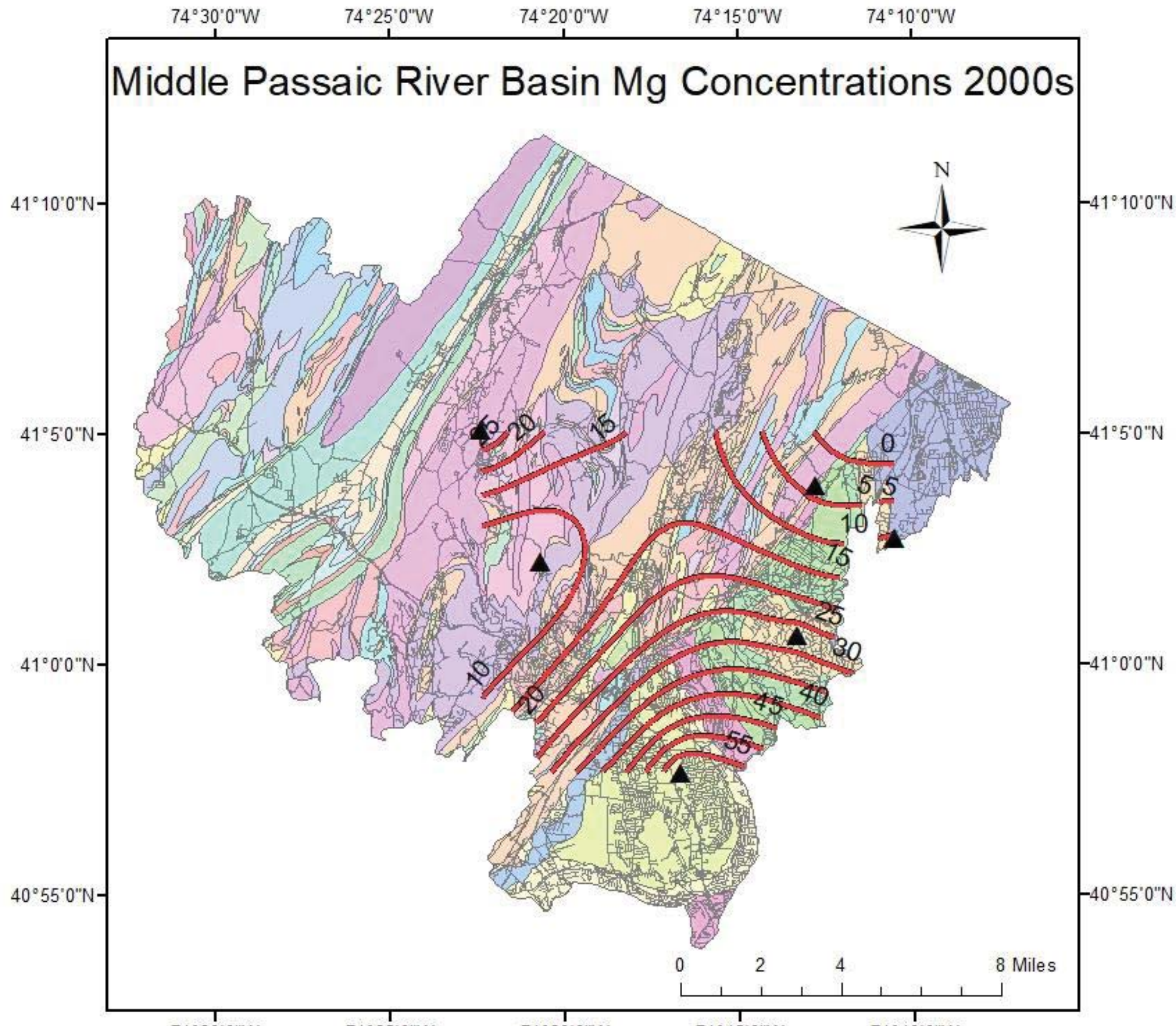

Figure 23c. Middle Passaic River Basin Mg concentration contour map for the 2000s.

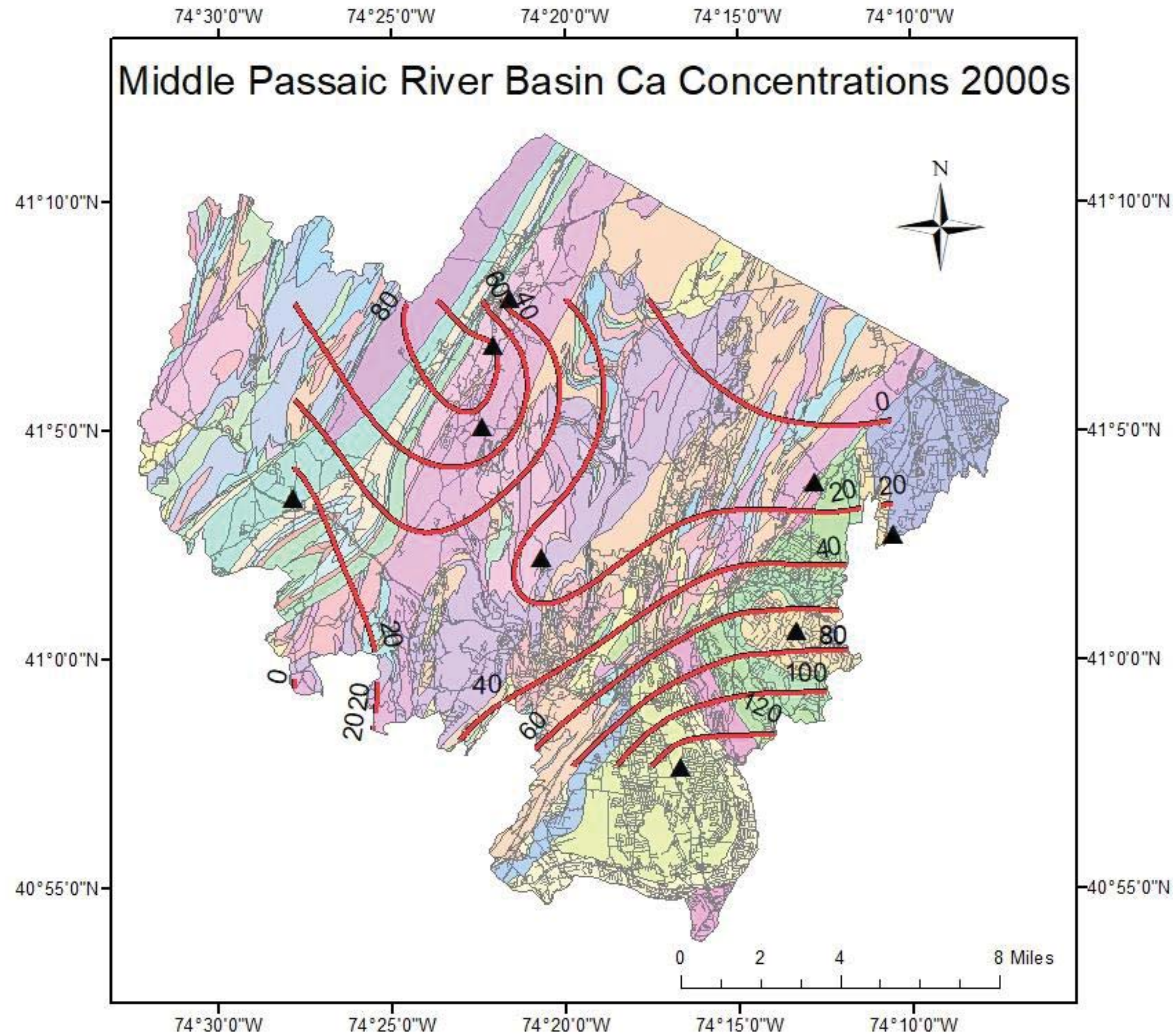

Figure 23d. Middle Passaic River Basin Ca concentration contour map for the 2000s.

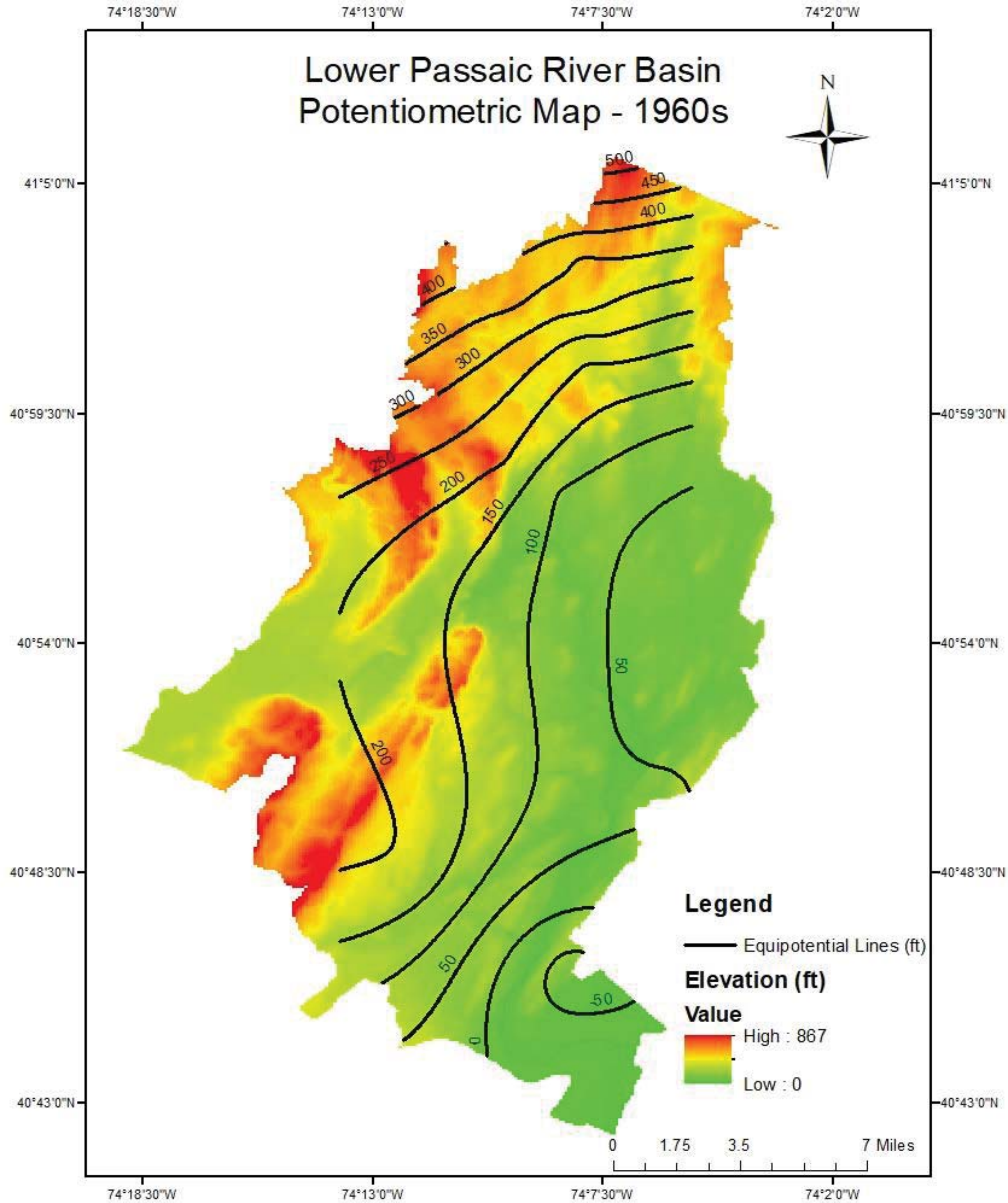

Figure 24a. Lower Passaic River Basin hydraulic head potentiometric map for the 1960s.

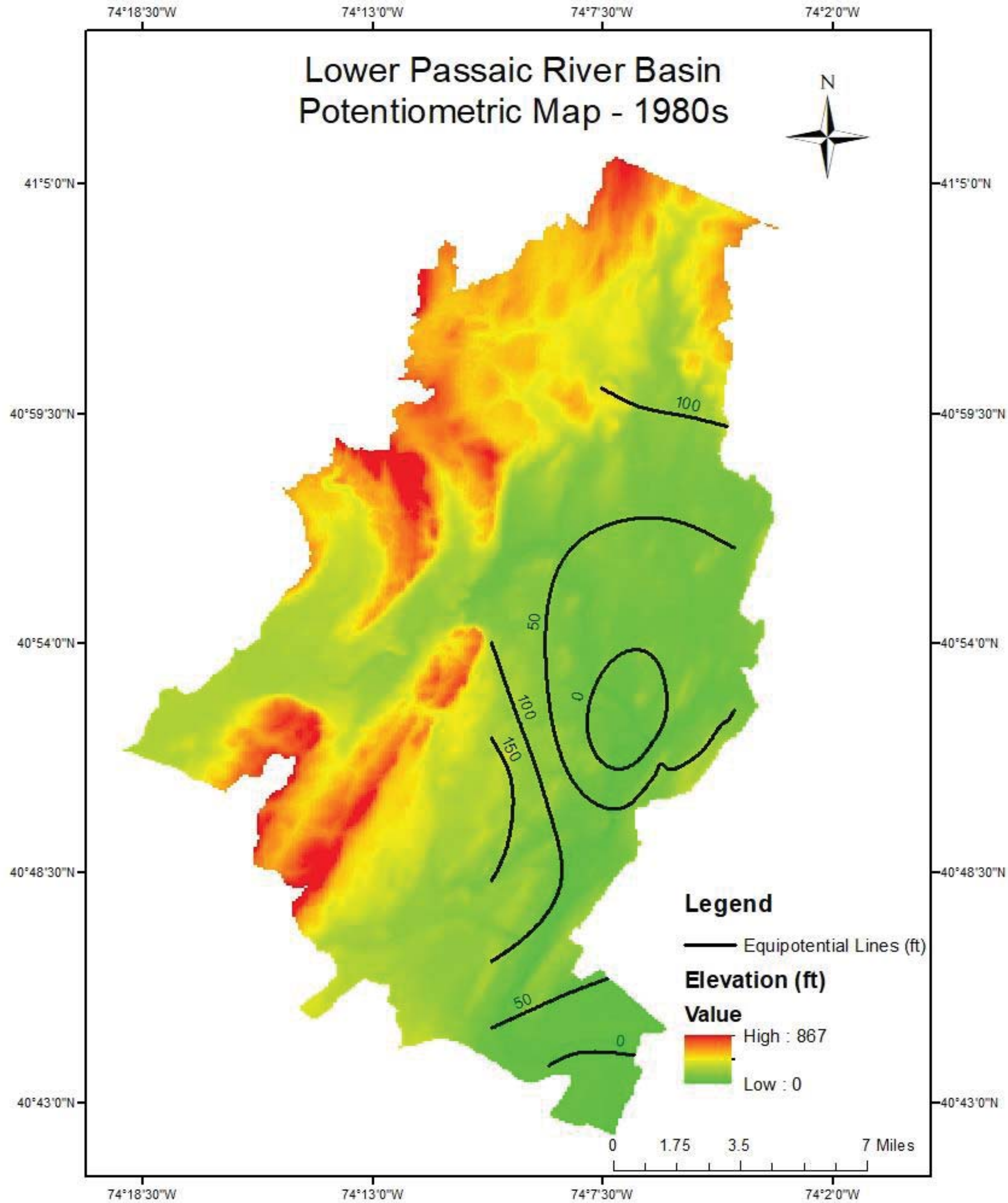

Figure 24b. Lower Passaic River Basin hydraulic head potentiometric map for the 1980s.

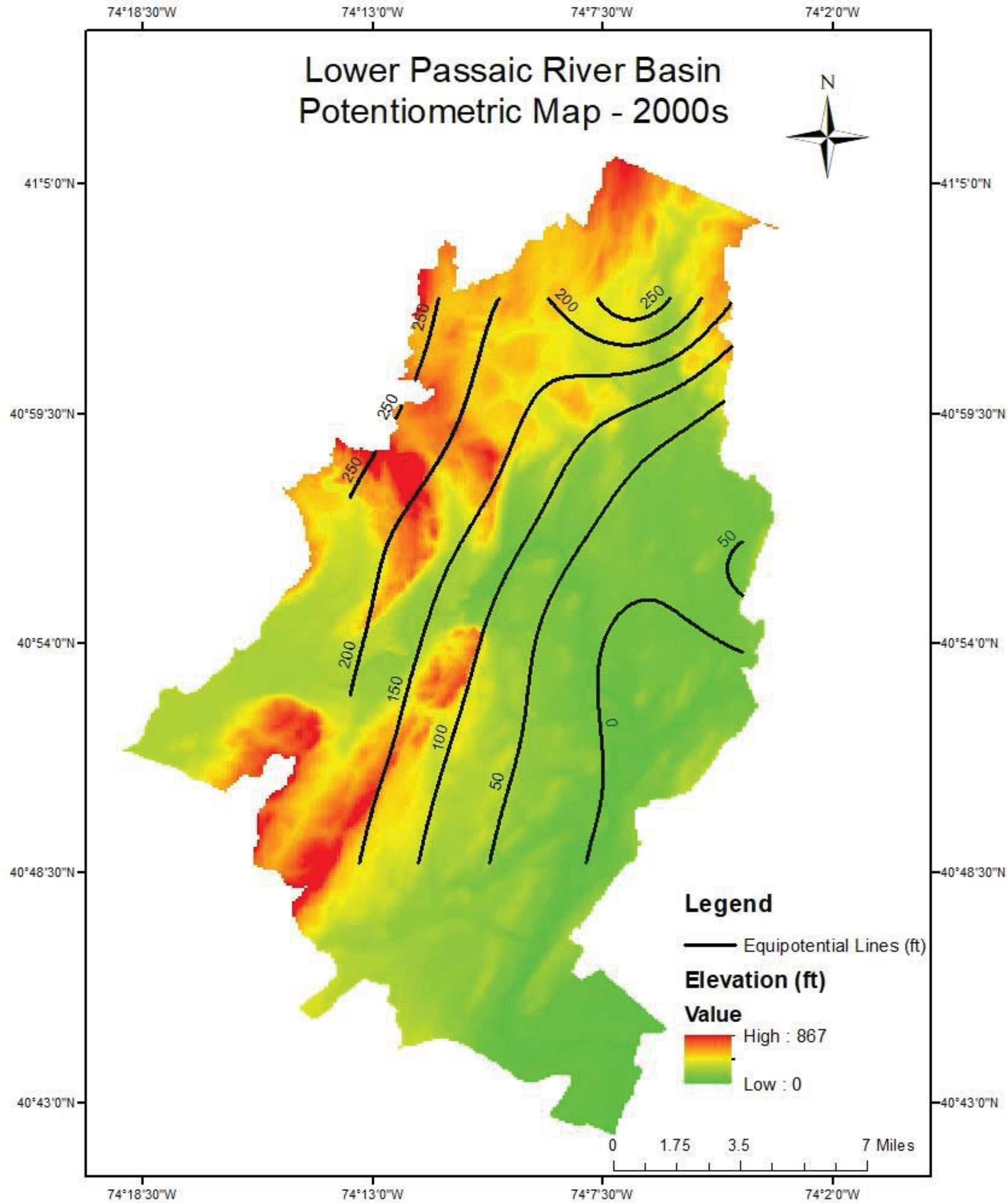

Figure 24c. Lower Passaic River Basin hydraulic head potentiometric map for the 2000s.

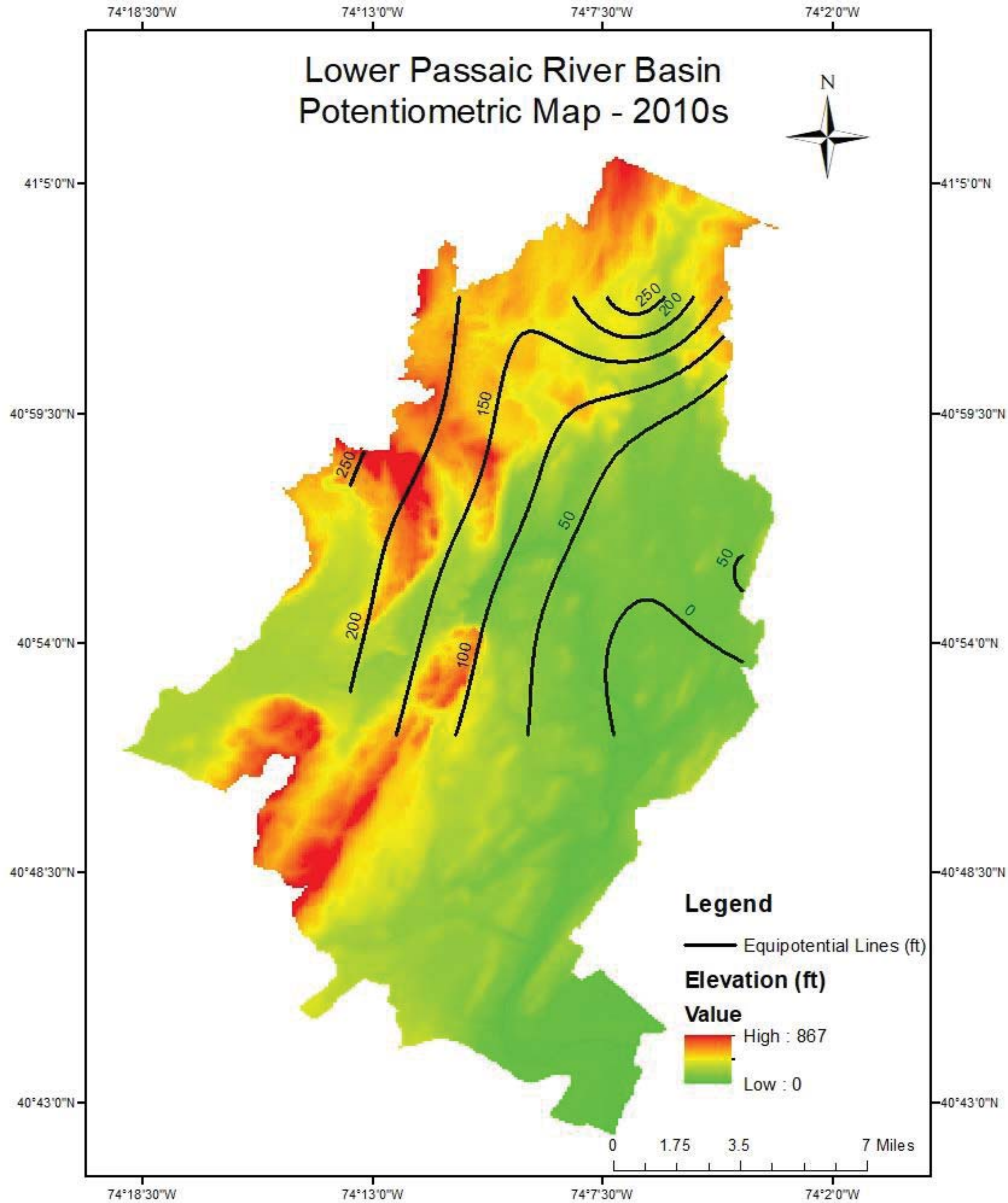

Figure 24d. Lower Passaic River Basin hydraulic head potentiometric map for the 2010s.

Legend

▲ Well Sites

Ion Concentration Contour in mg/L

LPRB Geology

Rock Classification

- basalt, fine- to coarse-grained
- basalt, fine- to medium-grained
- conglomeratic sandstone
- quartzite conglomerate, sandstone
- sandstone and siltstone
- sandstone, siltstone and shale
- sandstone, siltstone, silty mudstone, fine- to coarse-grained, and less abundant calcareous siltstone and mudstone, carbonaceous limestone
- sandstone, siltstone, silty mudstone, fine- to medium-grained; less abundant calcareous siltstone and mudstone
- sandy mudstone
- siltstone and shale

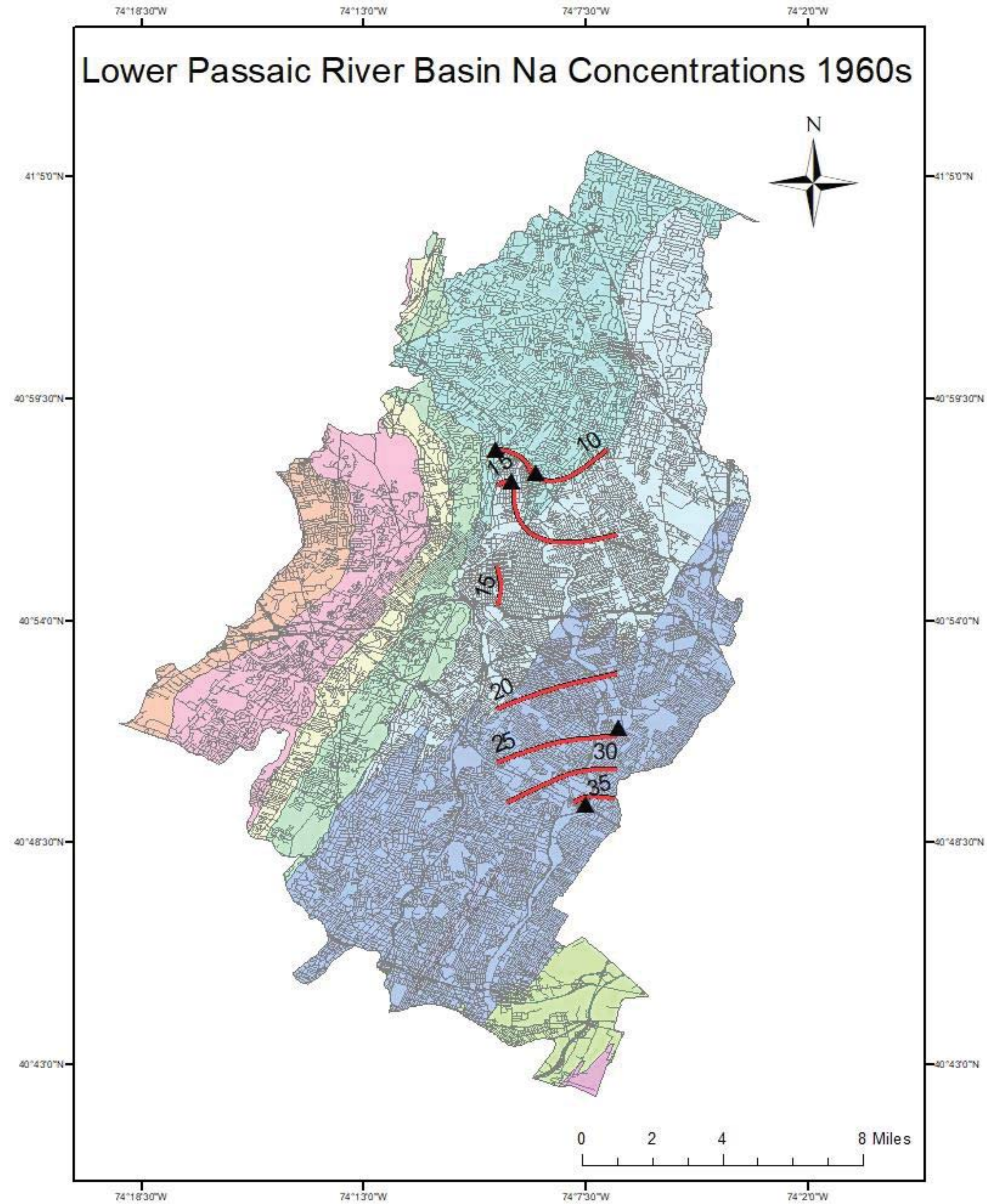

Figure 25a. Lower Passaic River Basin Na concentration contour map for the1960s.

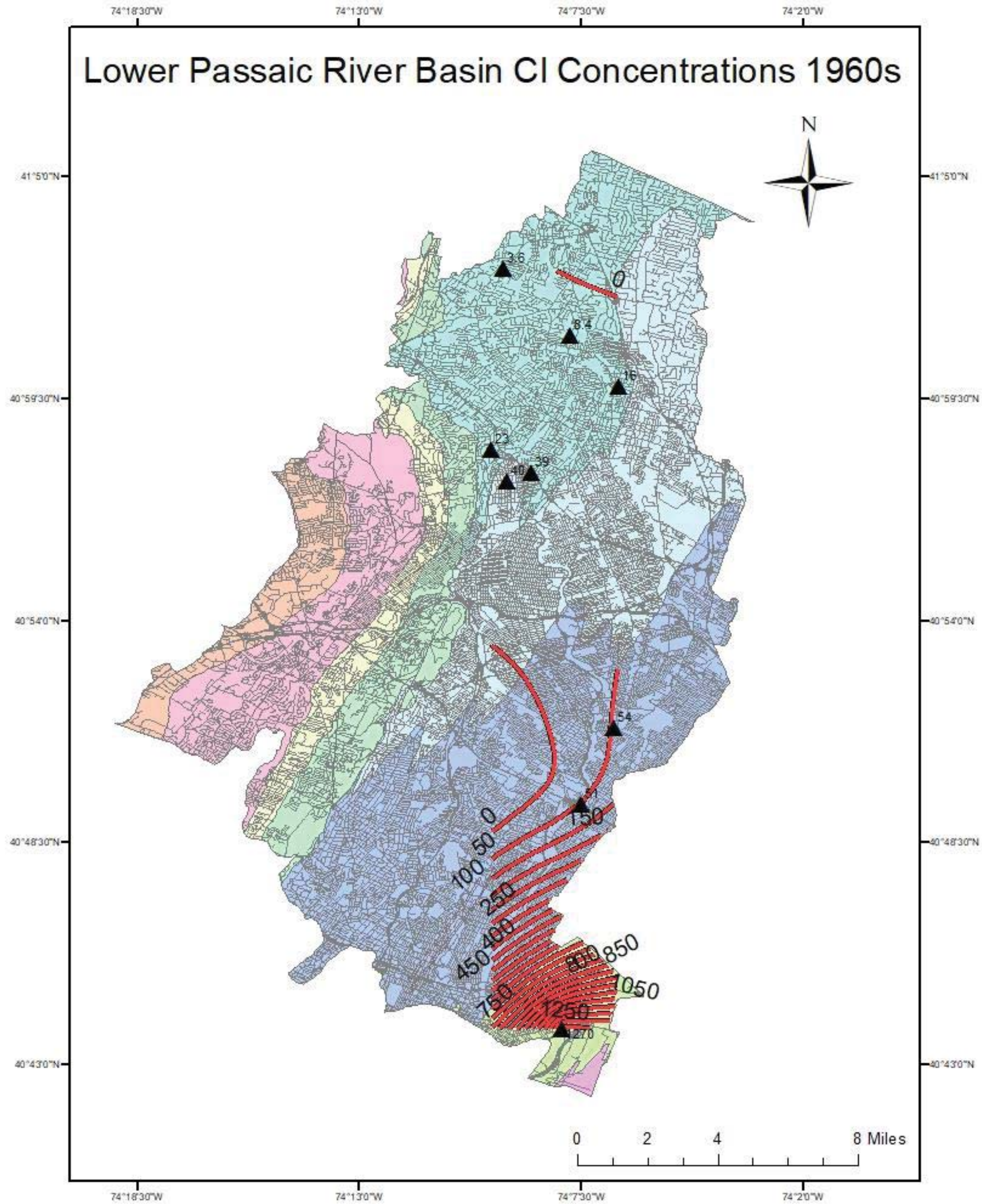

Figure 25b. Lower Passaic River Basin Cl concentration contour map for the 1960s.

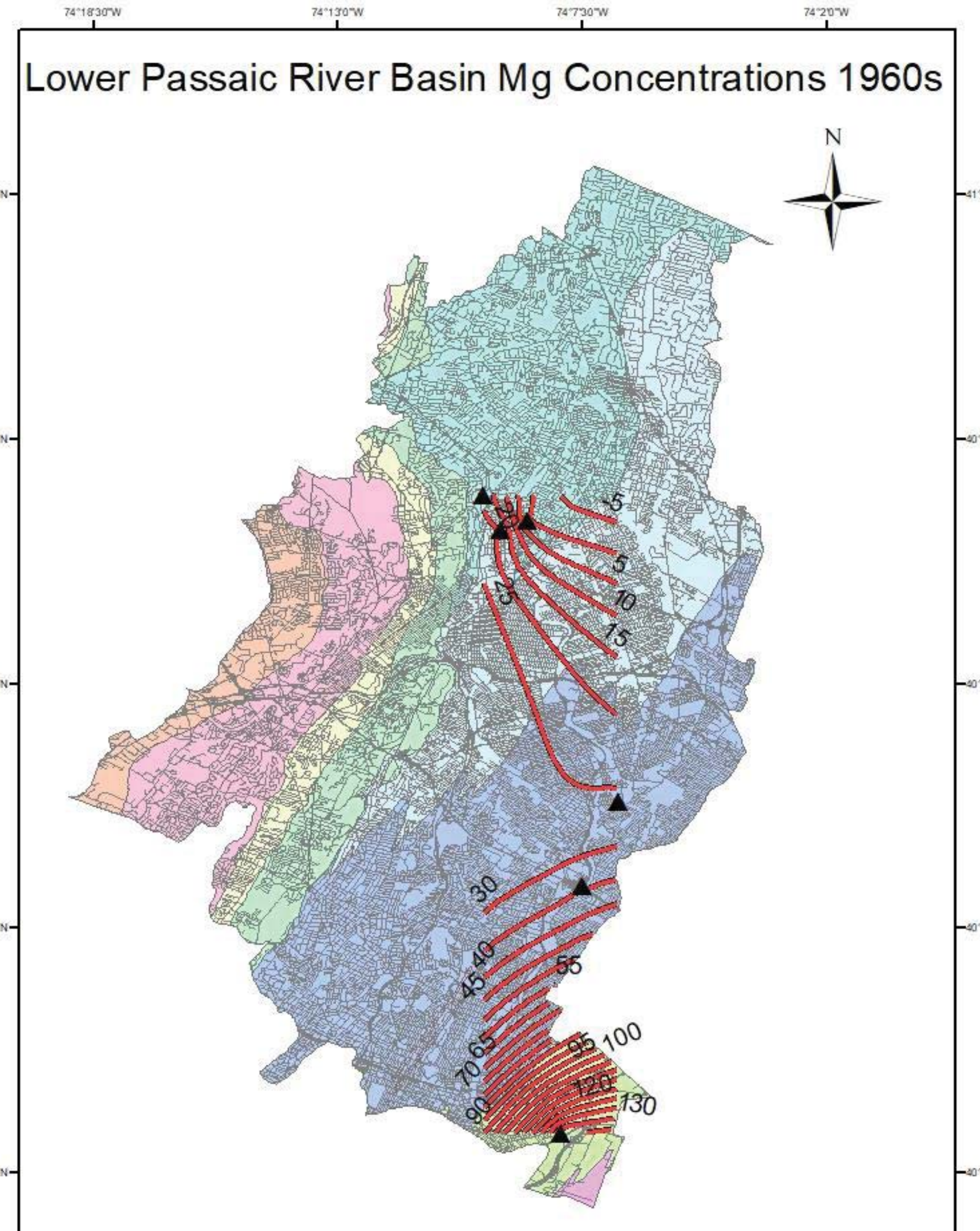

Figure 25c. Lower Passaic River Basin Mg concentration contour map for the 1960s.

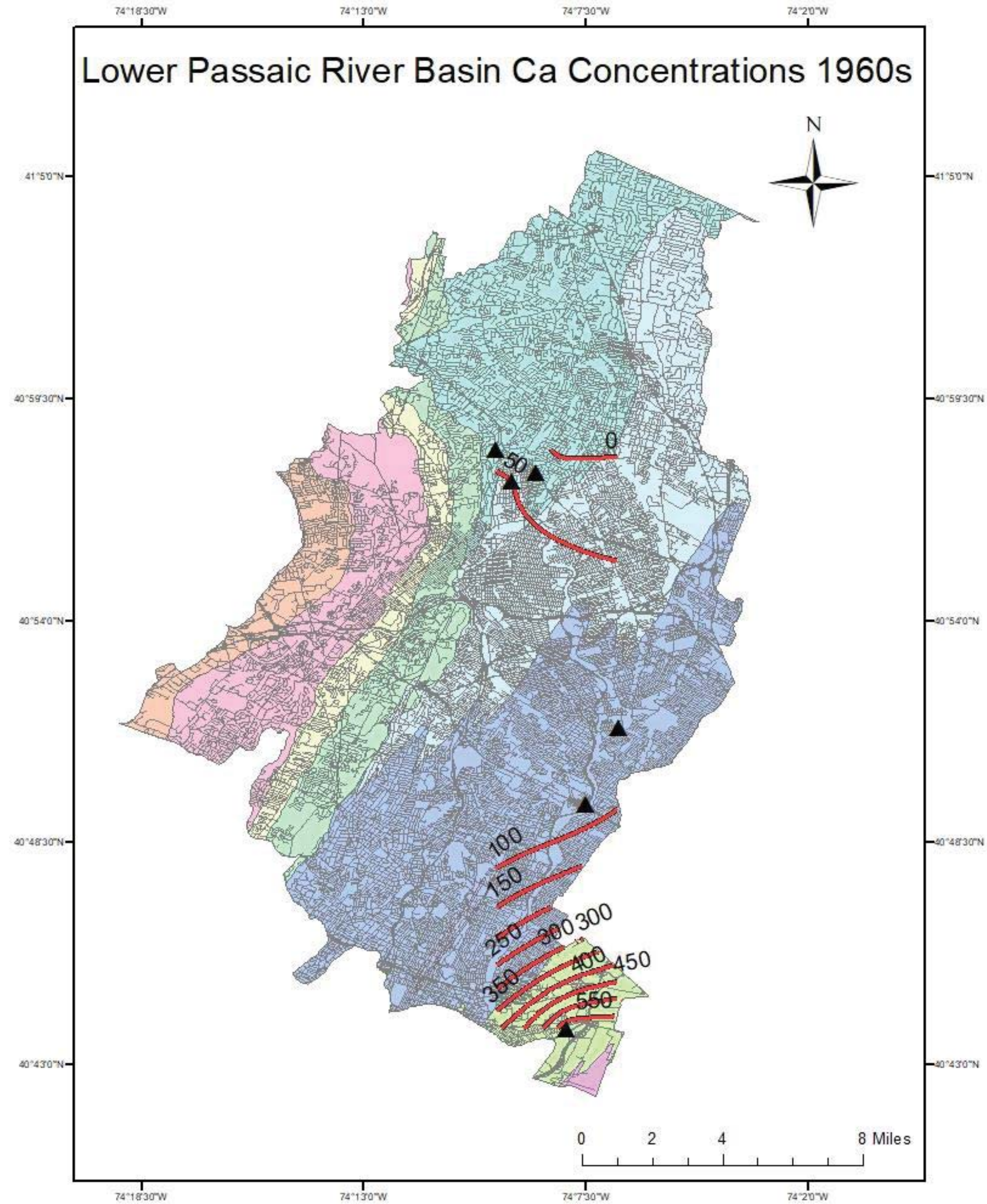

Figure 25d. Lower Passaic River Basin Ca concentration contour map for the 1960s.

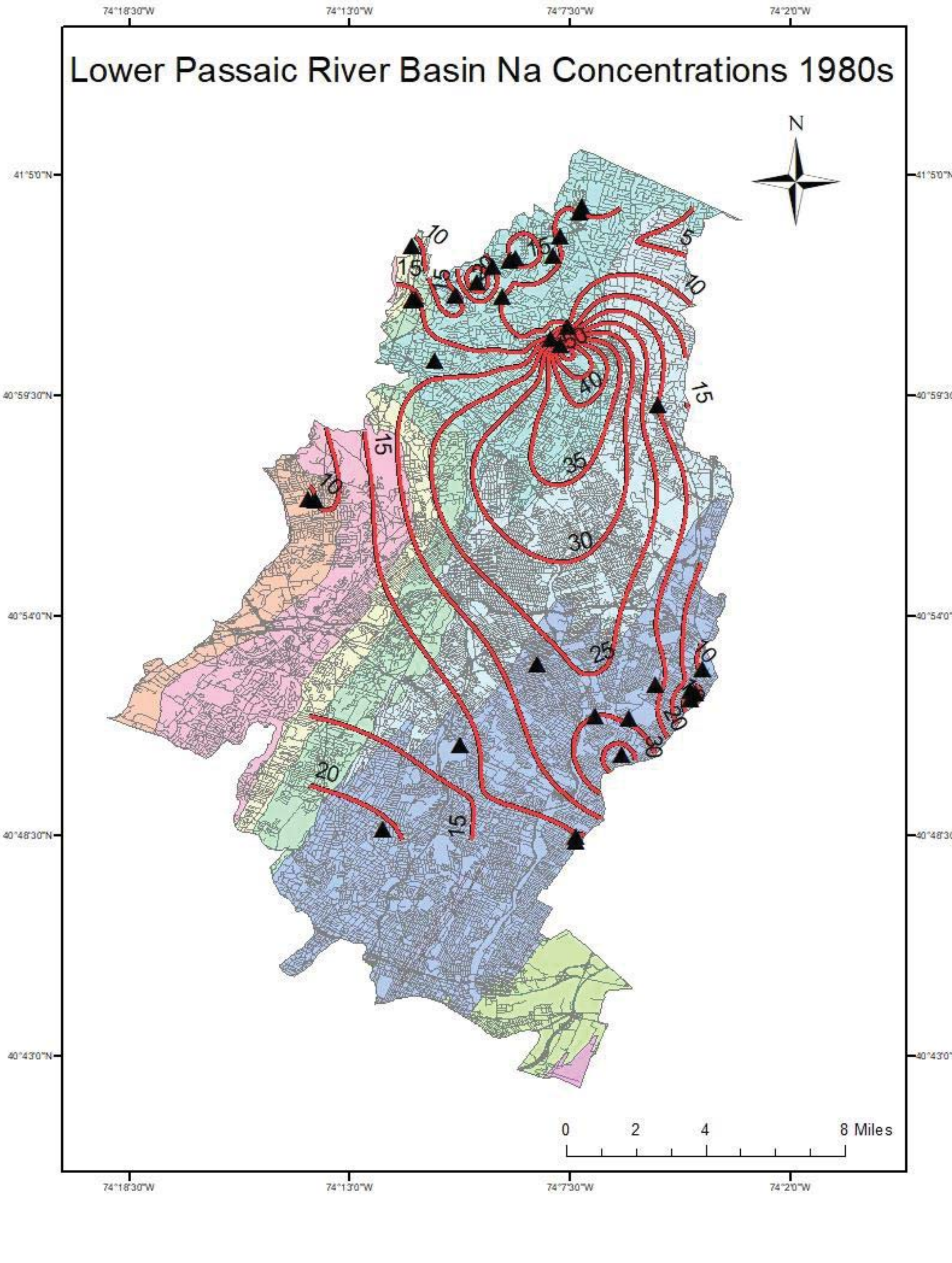

Figure 26a. Lower Passaic River Basin Na concentration contour map for the 1980s.

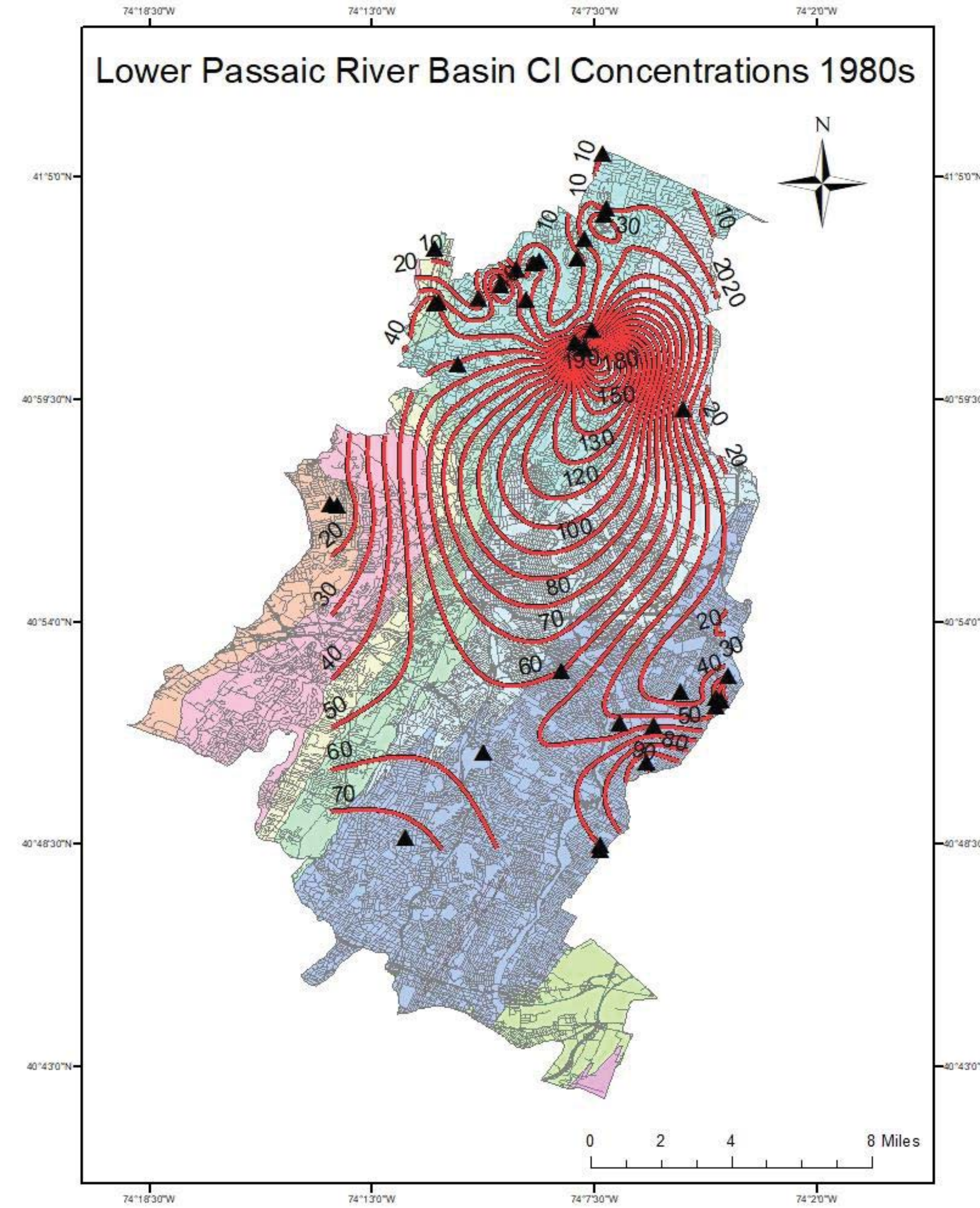

Figure 26b. Lower Passaic River Basin Cl concentration contour map for the 1980s.

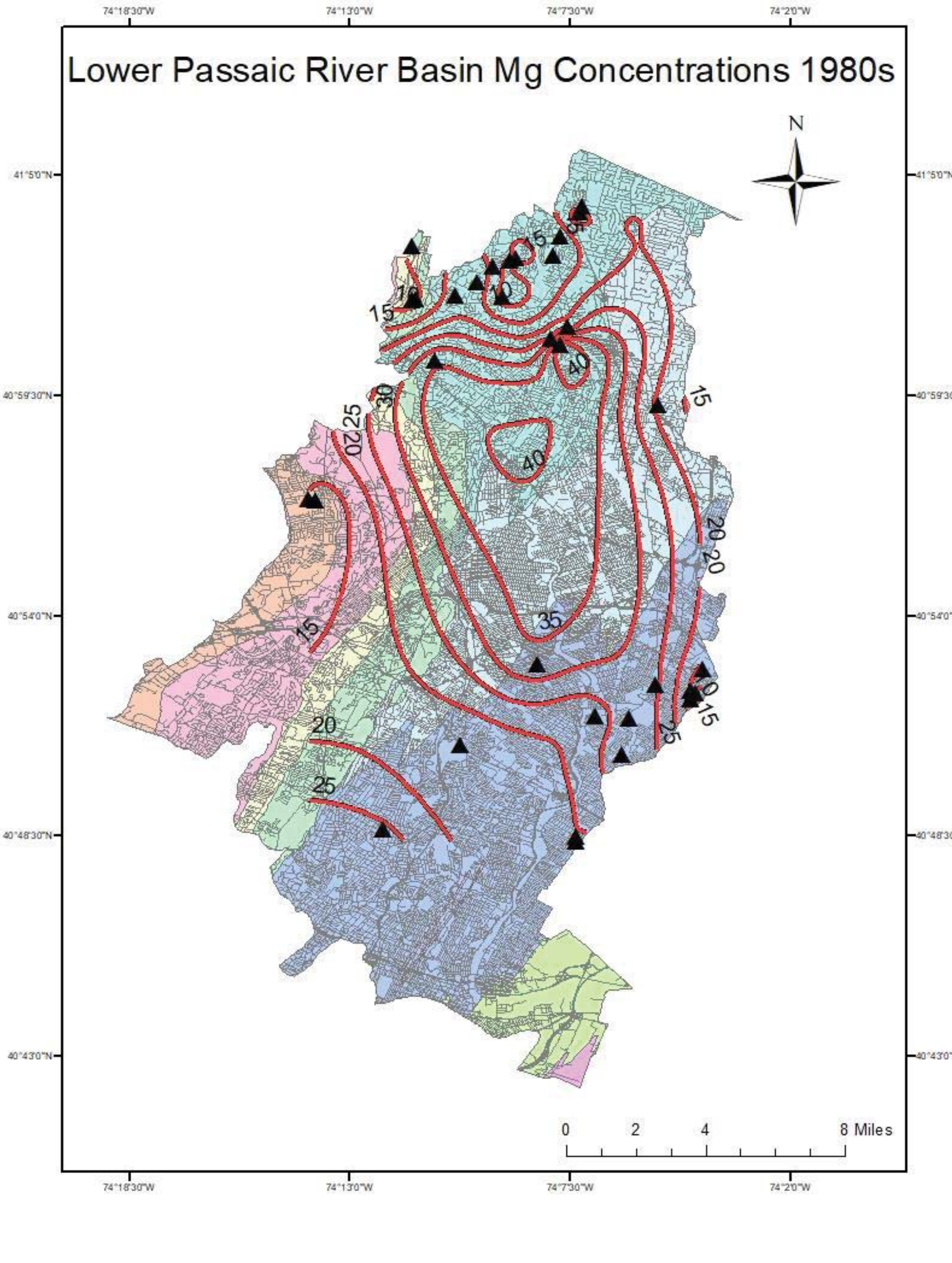

Figure 26c. Lower Passaic River Basin Mg concentration contour map for the 1980s.

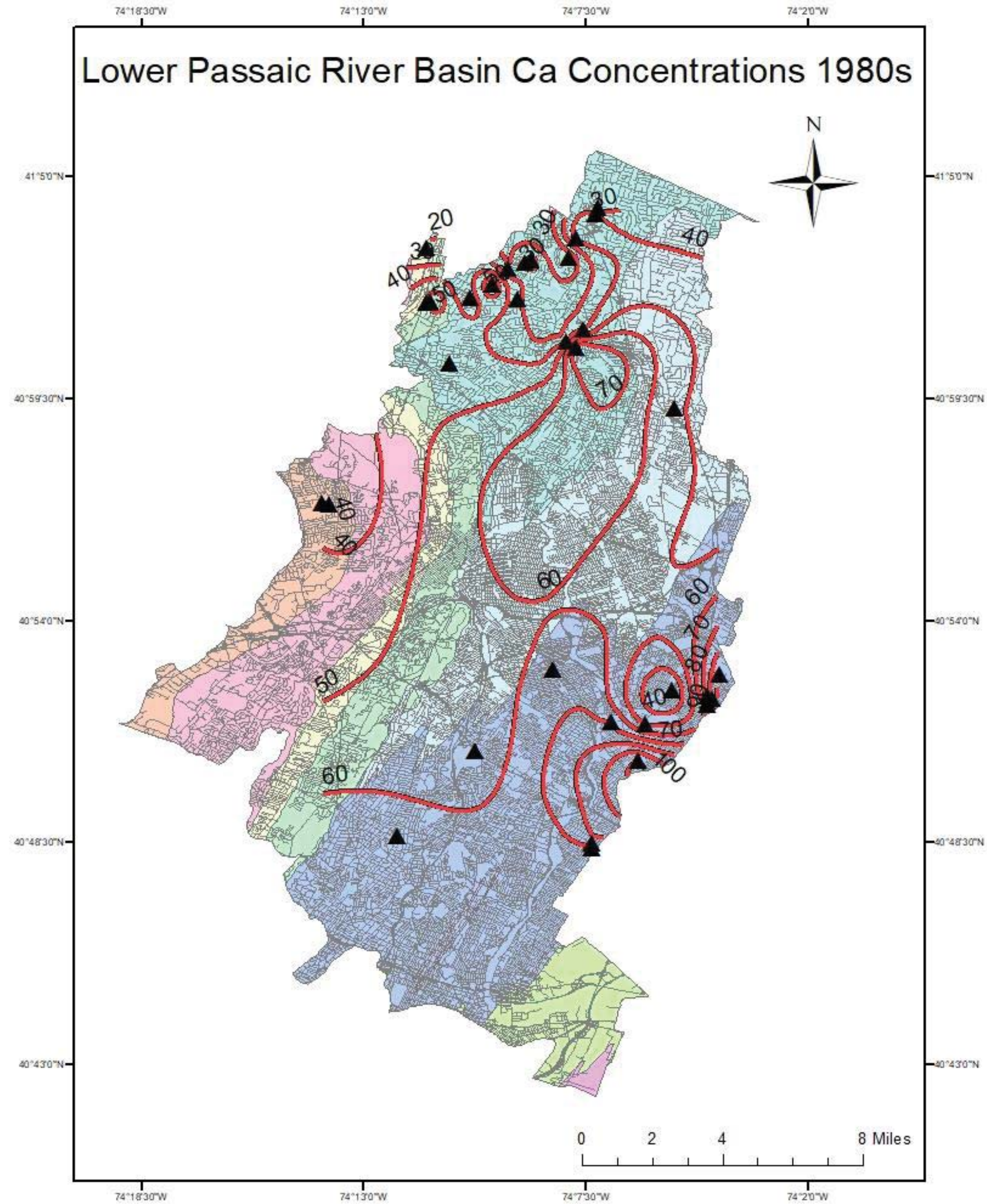

Figure 26d. Lower Passaic River Basin Ca concentration contour map for the 1980s.

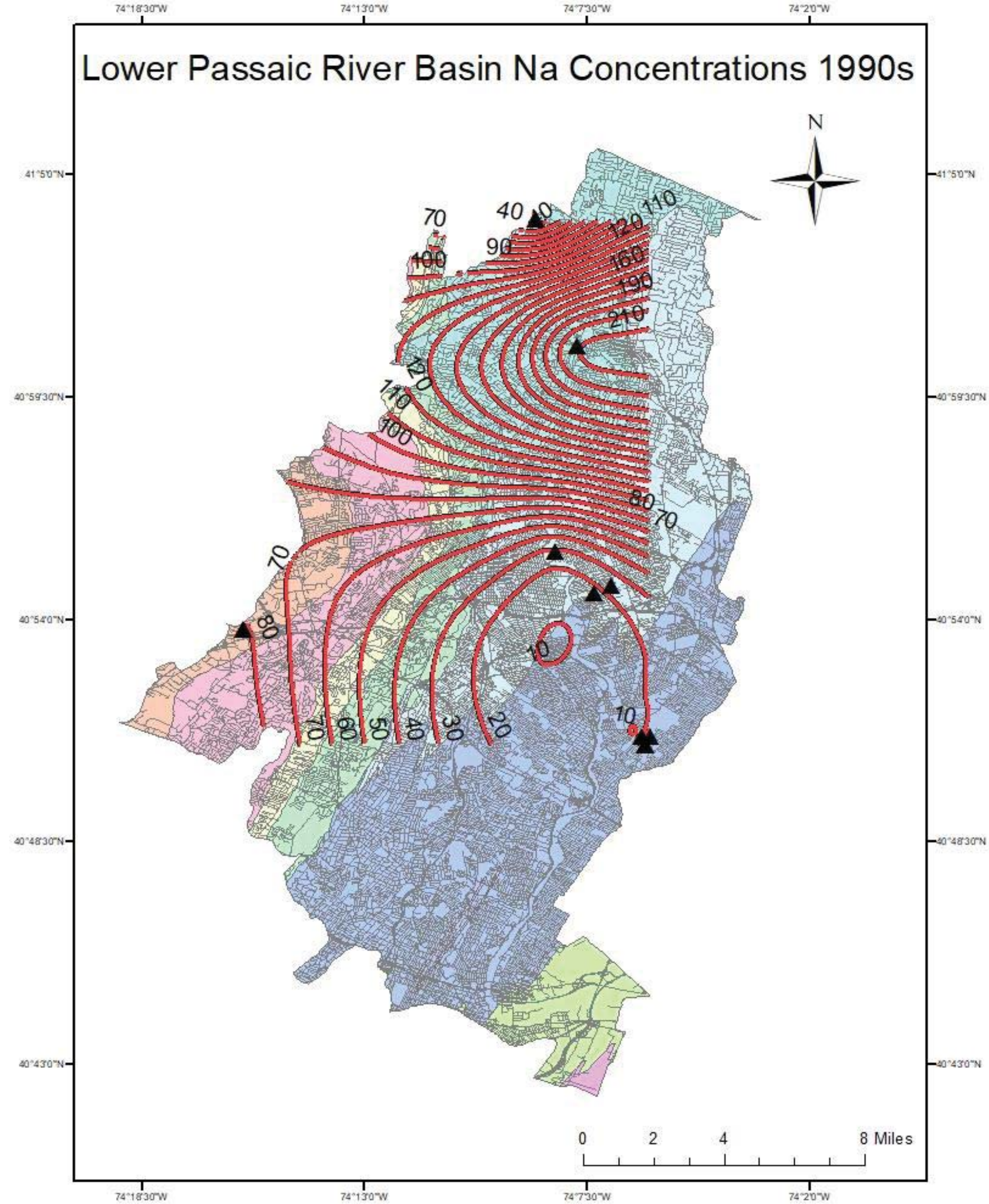

Figure 27a. Lower Passaic River Basin Na concentration contour map for the 1990s.

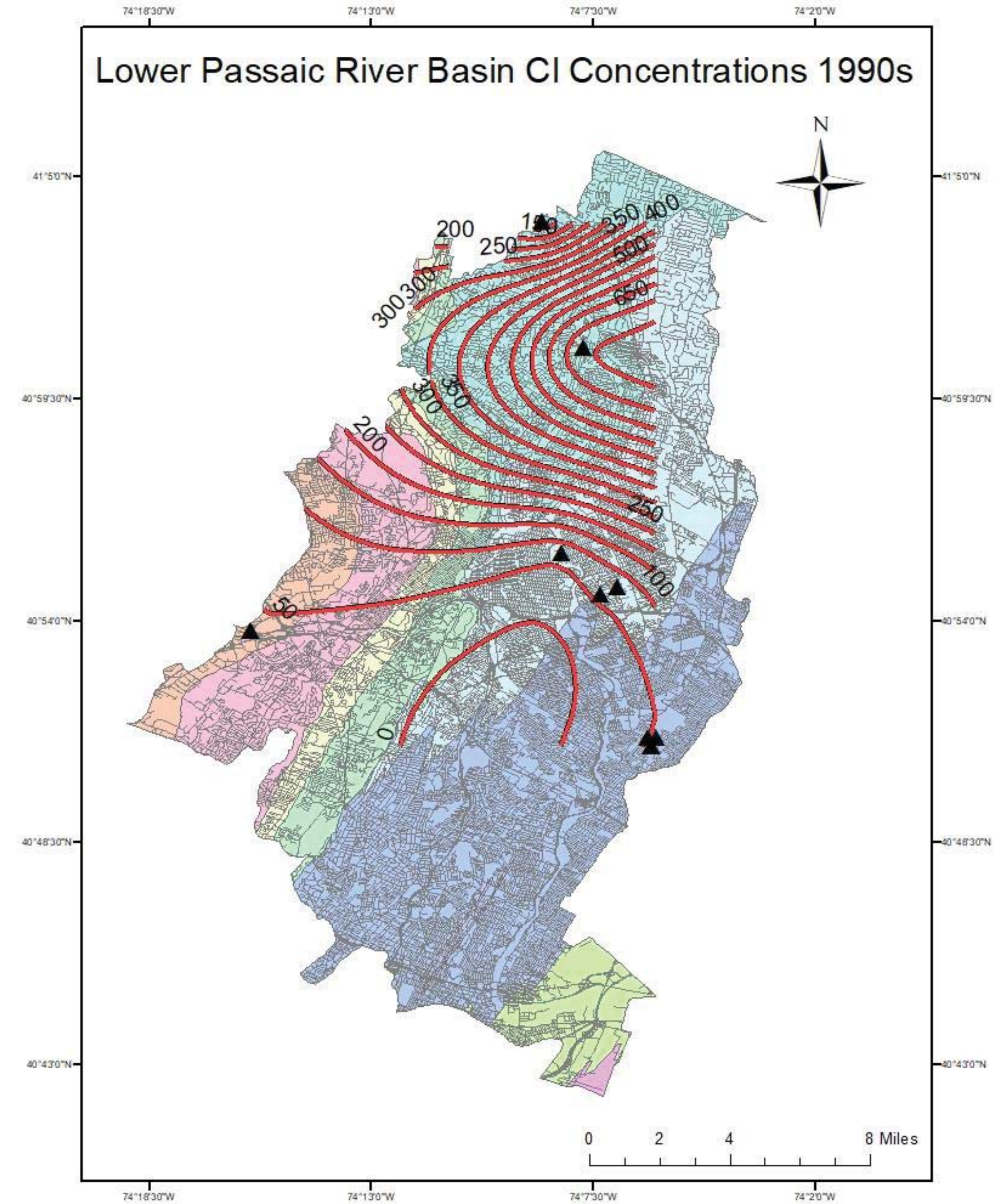

Figure 27b. Lower Passaic River Basin Cl concentration contour map for the 1990s.

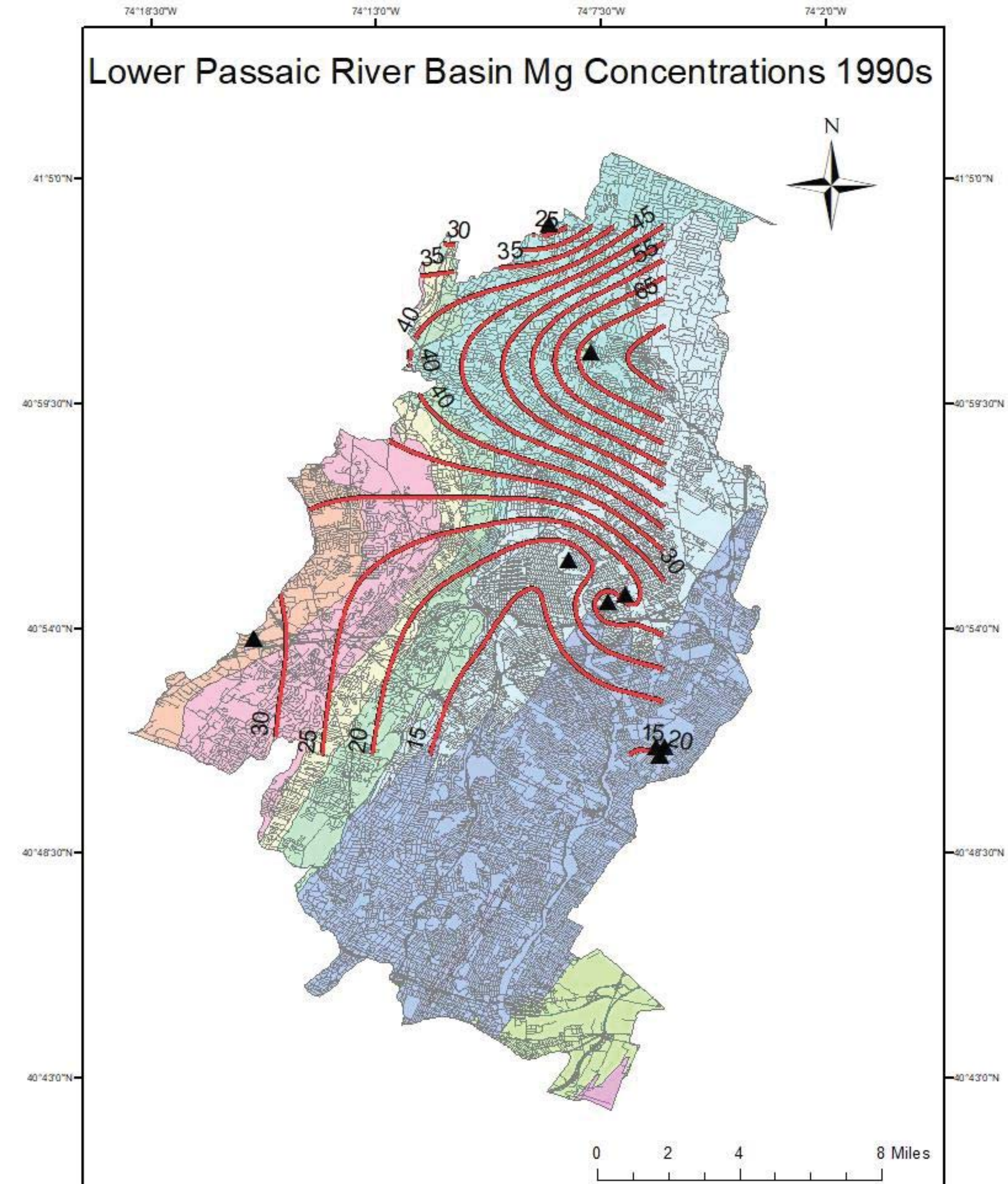

Figure 27c. Lower Passaic River Basin Mg concentration contour map for the 1990s.

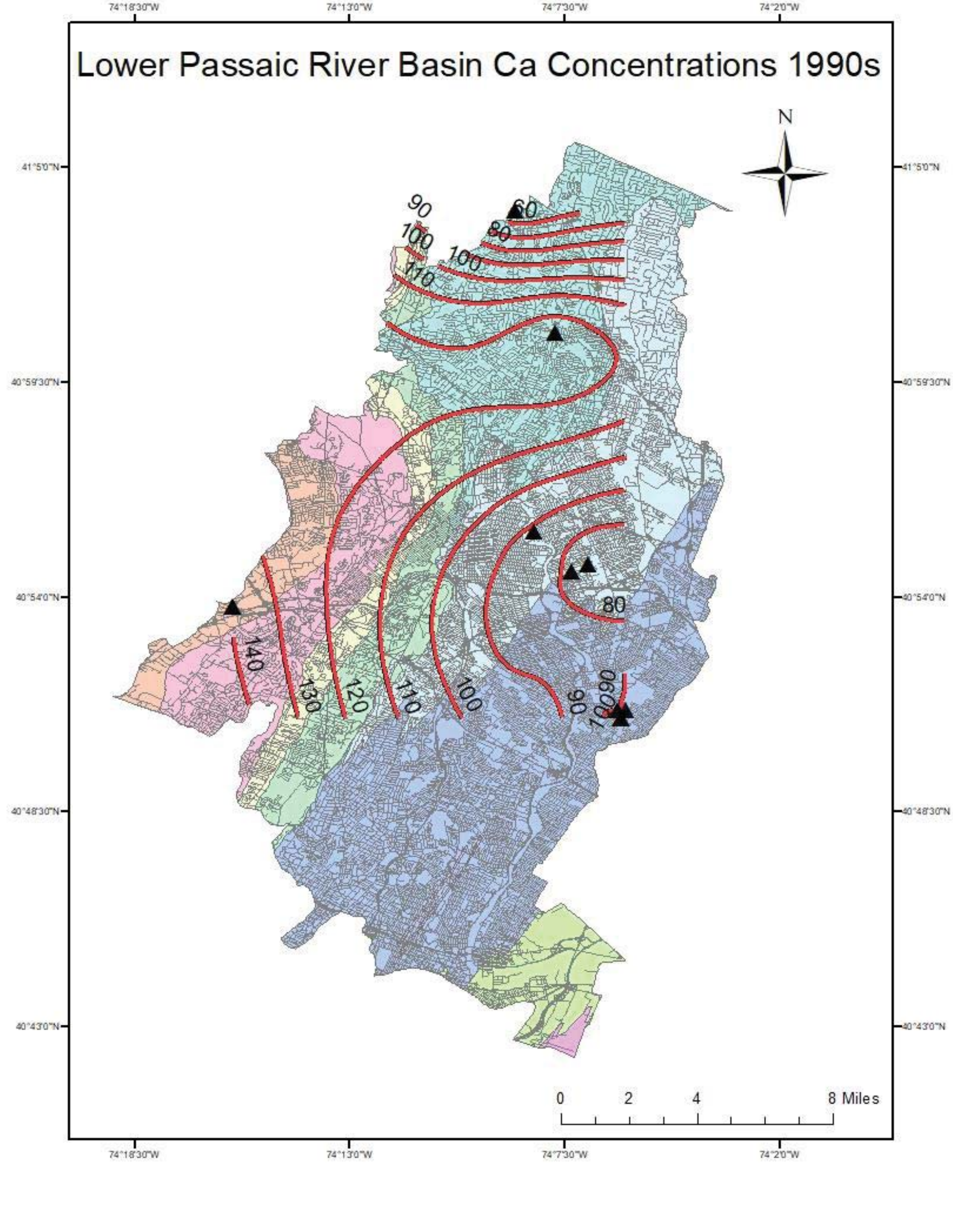

Figure 27d. Lower Passaic River Basin Ca concentration contour map for the 1990s.

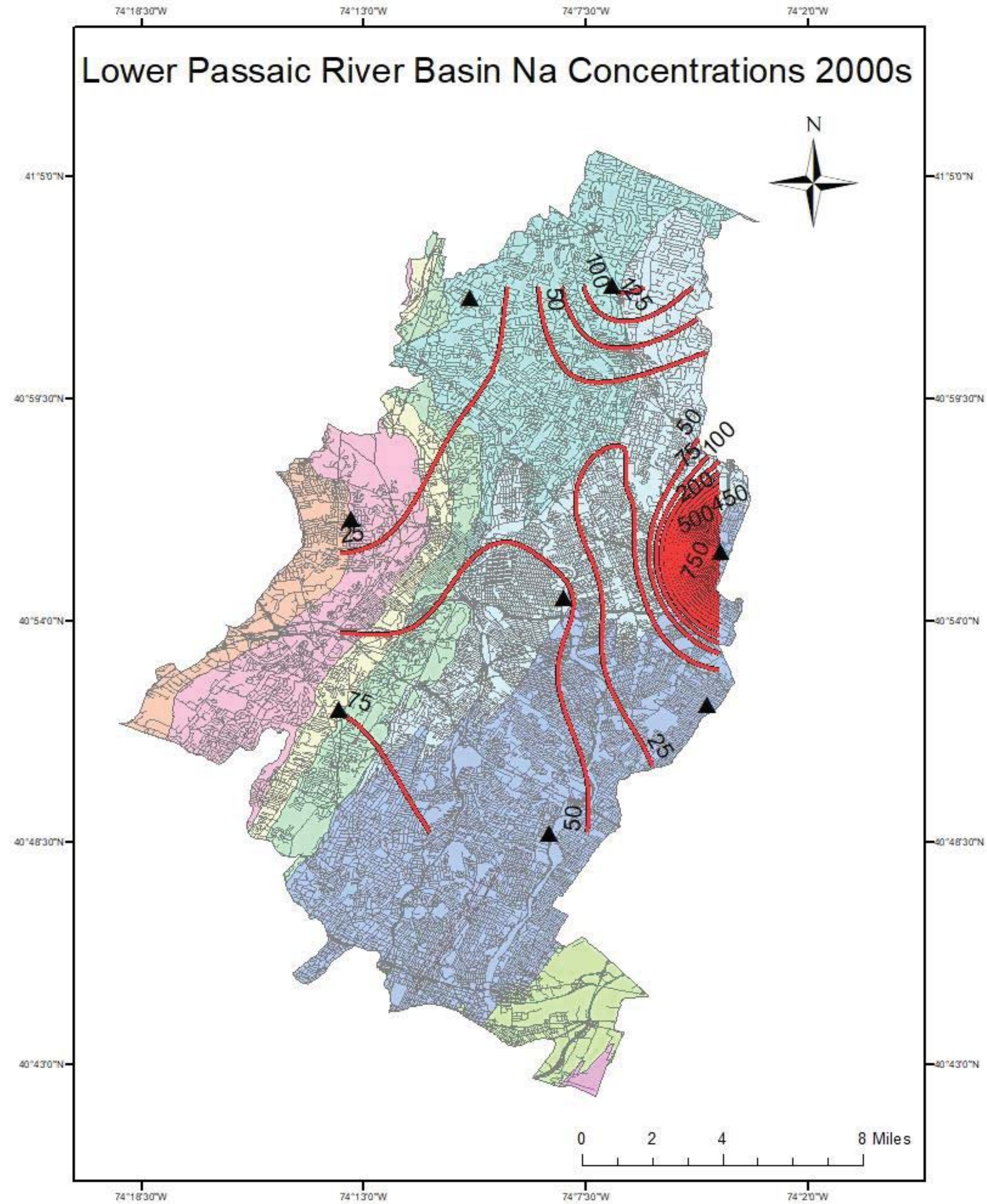

Figure 28a. Lower Passaic River Basin Na concentration contour map for the 2000s.

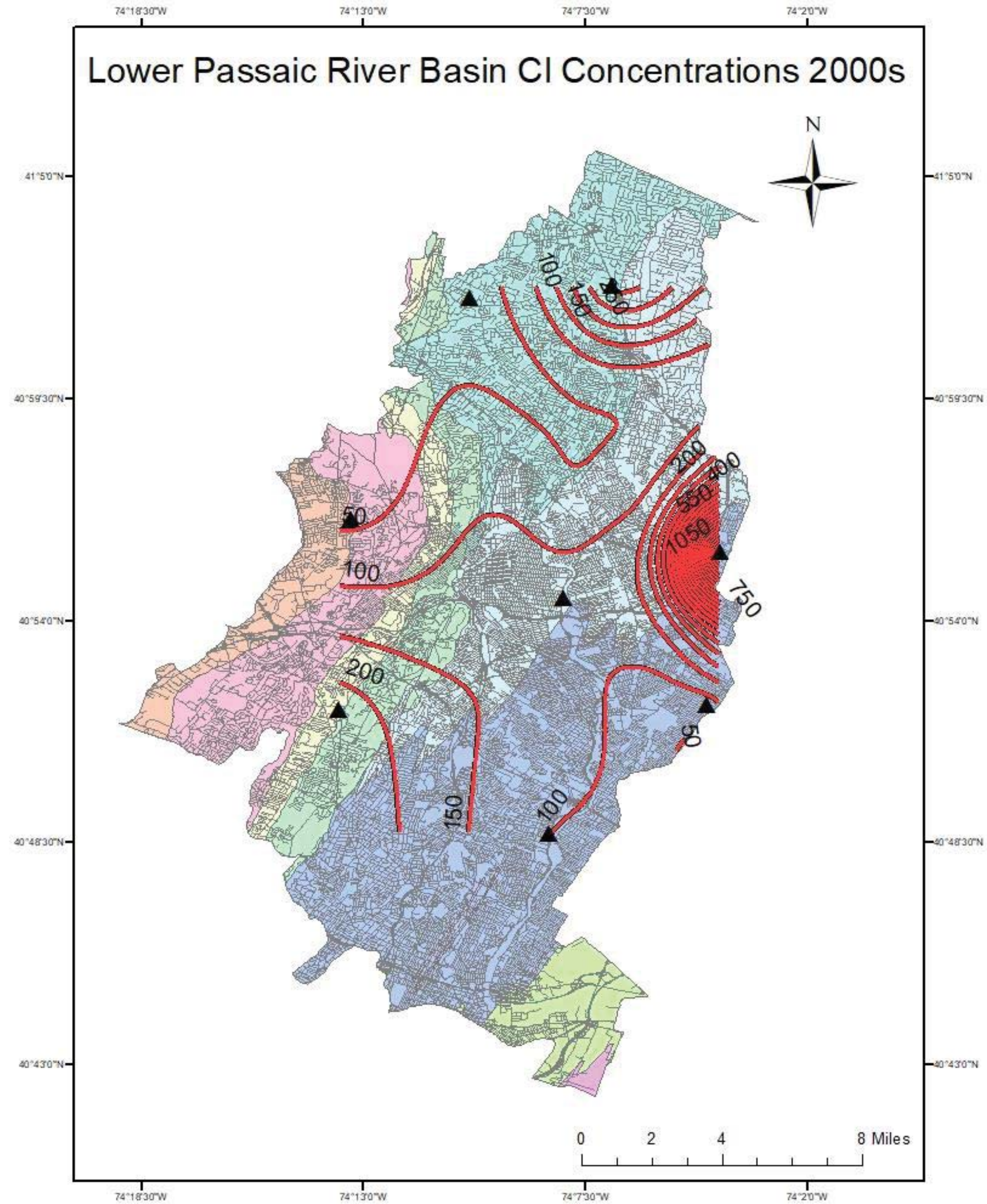

Figure 28b. Lower Passaic River Basin Cl concentration contour map for the 2000s.

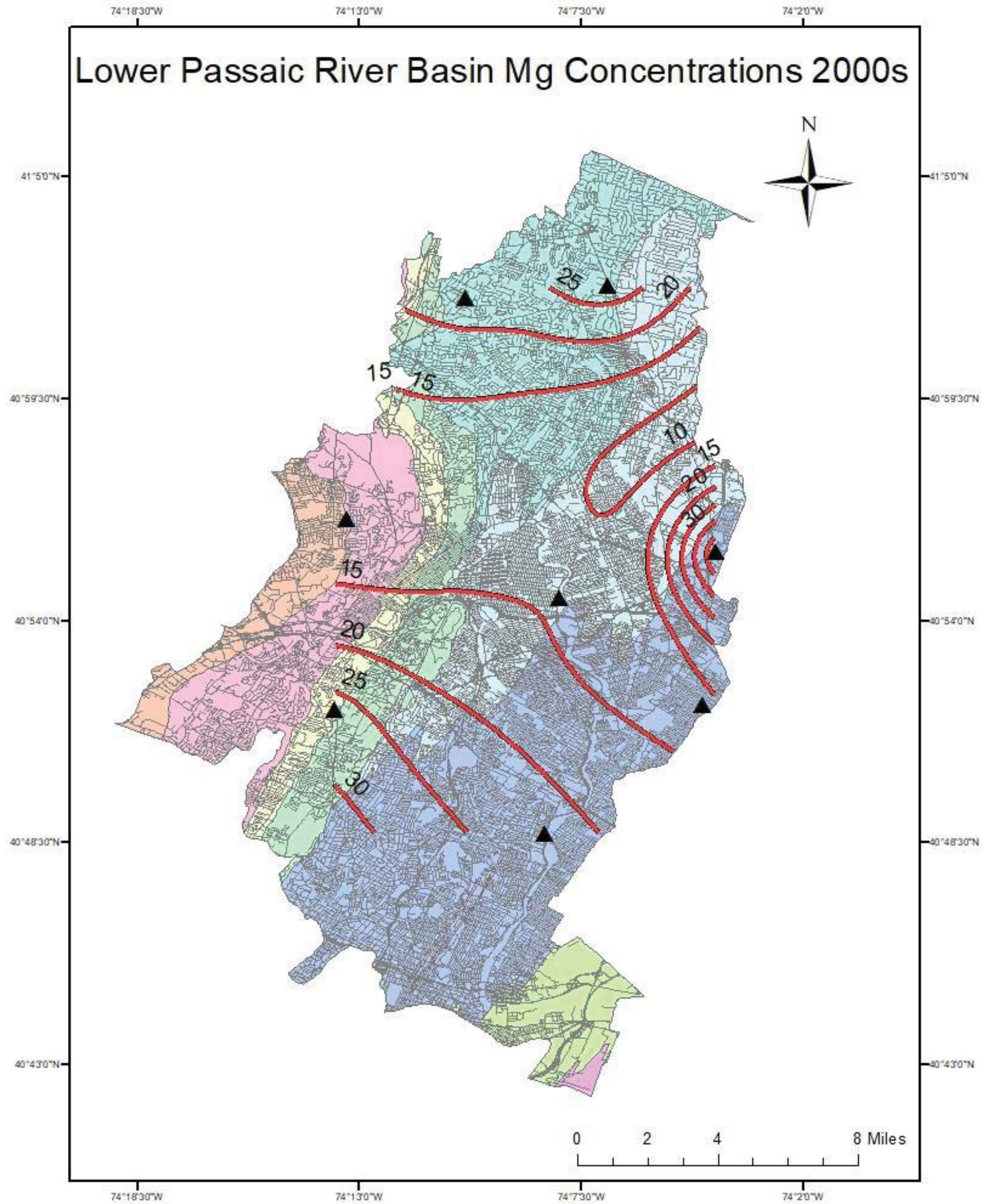

Figure 28c. Lower Passaic River Basin Mg concentration contour map for the 2000s.

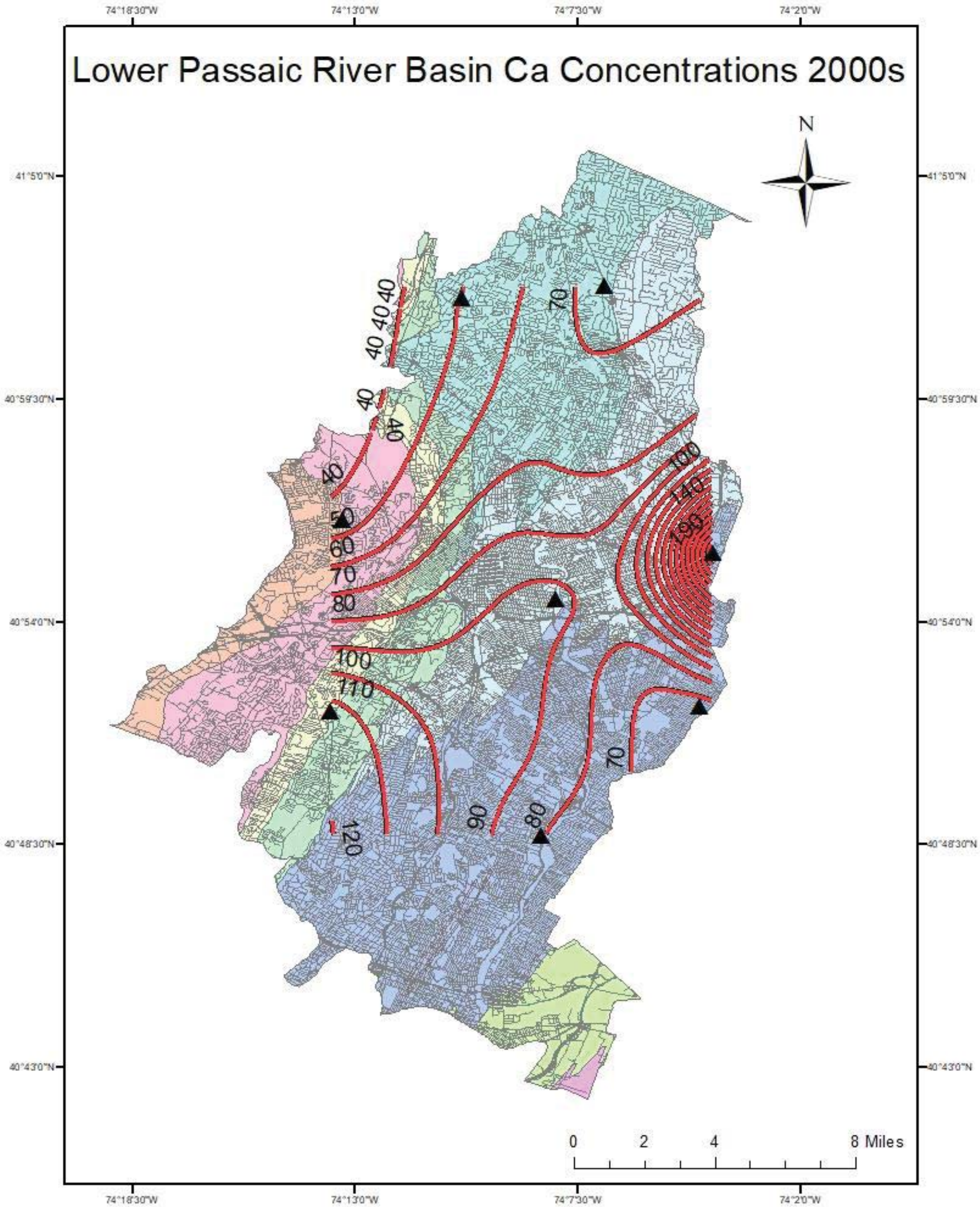

Figure 28d. Lower Passaic River Basin Ca concentration contour map for the 2000s.

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Appendix 1. Hydraulic Head data collected from the USGS for the Middle Passaic River Basin

SiteName	Field Measurement Date	Land Surface Elevation Above NGVD29 (ft)	Well Depth Below Land Surface (ft)	Water Depth Below Land Surface (ft)	Hydraulic Head (ft)	Latitude	Longitude
030148-- Com 1	5/5/1960	265	70	5	260	41.099263	-74.163478
310058-- Institutional 1	5/10/1960	420	413	22	398	41.093707	-74.265148
030251-- Dom 1	7/18/1960	280	90	40	240	41.067319	-74.212646
030254-- Dom 1	2/9/1962	490	165	10	480	41.007597	-74.227368
030244-- Dom 1	5/15/1962	435	39	15	420	40.99982	-74.232369
030250-- Com 1	11/7/1962	430	87	8	422	40.993709	-74.213479
030236-- Camp Yaw Paw 2	12/7/1962	780	86	9	771	41.085652	-74.227091
030240-- Dom 1	1/15/1963	450	125	35	415	41.017042	-74.230147
030153-- Dom	2/22/1963	325	308	20	305	41.062319	-74.176534
030077-- Dom	3/21/1964	290	265	60	230	41.053708	-74.21598
271114-- BOE	8/22/1964	400	413	145	255	40.916765	-74.340984
030059-- Dom	9/10/1964	260	235	20	240	41.066485	-74.205424
030242-- Dom 1	10/25/1964	430	45	15	415	41.013986	-74.225146
030252-- Dom 1	11/27/1964	380	140	36	344	41.069819	-74.161256
030174-- Elbert St	5/17/1965	340.3	400	2	338.3	41.067596	-74.149588
030028-- 4096	8/1/1965	450	320	50	400	41.055097	-74.183201
030238-- Dom 1	10/26/1965	380	135	20	360	41.045097	-74.175978
030037-- Hilltop Ter TW	3/3/1966	430	330	48.42	381.58	40.996486	-74.236813
310054-- 1 Of 3	6/28/1966	970	206	30	940	41.09593	-74.379597
030241-- Dom 1	8/13/1966	415	98	15	400	41.014542	-74.21459
030189-- Irr	9/17/1966	450	90	35	415	41.003709	-74.242091
030068-- Dom	10/5/1966	265	148	16	249	41.081207	-74.179034
310009-- PW 5	1/24/1967	440	186	90	350	41.122318	-74.244592
030034-- Spring St	2/3/1967	345	600	-5	350	41.074096	-74.142172
030184-- PW 9	8/1/1967	305	150	-25	330	41.026153	-74.229813
030142-- Fyke Rd 1	1/10/1969	420	513	2	418	41.059541	-74.193201
030253-- Dom 1	1/15/1969	430	215	30	400	41.010375	-74.222646
310016-- Lincoln Ave 2	11/17/1969	170	153	-4	174	40.981014	-74.283509

271115-- PW 2	10/22/1970	220	196	24	196	40.978987	-74.308205
310093-- Meadowbrook 1	5/12/1971	250	105	5.11	244.89	41.055374	-74.281815
030187-- Rec 1	1/10/1972	212.3	98	22	190.3	41.020375	-74.25737
030191-- Rec 1	5/4/1972	210	50	10	200	41.016764	-74.259592
030180-- Rec 1	5/16/1973	218	52	12	206	41.015931	-74.256536
310055-- Awosting 3 - Wm 3040	11/29/1973	650	360	2	648	41.152595	-74.338485
270055-- Indian Lane 1	4/9/1974	190	242	-1.5	191.5	40.935015	-74.34365
030245-- Darlington Park 2	7/16/1974	320	300	30	290	41.062874	-74.176534
030053-- Dom	7/21/1975	260	130	15	245	41.064541	-74.21348
030050-- Dom	8/18/1975	270	270	60	210	41.065096	-74.21348
310177-- Institutional 10	10/3/1975	835	200	37	798	41.114263	-74.368486
030246-- Darlington Racquet 1	3/11/1977	405	300	50	355	41.066485	-74.181812
030248-- Dom 1	2/2/1978	520	168	18	502	41.060374	-74.22848
030237-- Dom 1	9/22/1978	365	260	40	325	41.071485	-74.160422
030038-- Franklin Lakes 1	1/11/1980	420	138	33.54	386.46	40.991764	-74.213201
030023-- PW 16	3/26/1980	246	149	25	221	41.085068	-74.183645
310060-- PW 4	4/19/1982	660	300	-10	670	41.159262	-74.328762
310057-- Concord Rd-Bald Eagle	10/18/1982	770	350	70	700	41.11093	-74.39182
030120-- WD 17	11/8/1982	250.9	169	9	241.9	41.085096	-74.181534
271113-- Indian Lane 3/Montvi 6	9/28/1984	200	203	16	184	40.935654	-74.33765
310142-- SUS 0139 Dom	6/28/1991	610	173	66	544	41.067389	-74.326111
310064-- Beattie Ln9	6/28/1991	610	173	66	544	41.068985	-74.282927
310143-- SUS 0122 Dom	8/2/1991	995	250	46	949	41.08475	-74.373667
310141-- SUS 0136 Dom	8/26/1992	850	152	28	822	41.055417	-74.459611
310144-- SUS 0107 Dom	9/10/1993	505	223	23	482	41.092444	-74.257833
310061-- Dc114	10/1/1993	180	230	-4.6	184.6	40.971765	-74.279593
310063-- Dc147	10/7/1993	185	13.6	10.14	174.86	40.970376	-74.278759
310067-- Du-147A	10/7/1993	185usgs	13.6	10.14	174.86	40.970376	-74.278759
310062-- Dc114A	10/11/1993	180	28	12.3	167.7	40.971765	-74.279593
310147-- SUS 0253 Dom	12/8/1994	805	150	8	797	41.034889	-74.392833
310146-- SUS 0080 Dom	1/20/1995	720	202	30	690	41.129444	-74.3585

030066-- Dom	10/27/1998	260	71	6.67	253.33	41.078152	-74.182367
310200-- MW137	4/18/2016	192	24	9.33	182.67	40.960833	-74.278333
270028-- Green Pond 5 Obs	11/15/2017	758.56	120	4.75	753.81	41.035375	-74.449599

Appendix 2. Groundwater quality measurements collected from the USGS for the Middle Passaic River Basin.

Sitenames	Sample Date	Specific Conductance (μ/cm)	pH	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Cl (mg/L)	SO_4 (mg/L)	TDS (mg/L)	Na (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	F (mg/L)	Latitude	Longitude
030014-- Bush 5	4/29/1959	245	7.8	32	7.3	0.5	7.4	20	154.4	6	106		0	41.023708	-74.250703
030004-- Dom 1	3/18/1964	364	7.6	34	16	0.2	25	24	228.0	15	128		0.1	41.070652	-74.187645
030017-- Drlngtn Well	5/19/1964	243	8.1	24	9.2	0	7.9	29	154.4	12	92	0	0	41.059597	-74.159089
030012-- Cent Av 1	5/19/1964	288	7.6	26	11	0	9.4	39	183.9	16	107	0	0.1	41.079818	-74.150978
030015-- Woodland Well	5/19/1964	278	7.7	36	9.7	0	6.9	23	176.5	6	136		0	41.054819	-74.164311
030009-- Soons 8	5/21/1964	184	7.1	23	5.1	0	8.3	20	125.0	5.1	73	0	0	41.050652	-74.224591
030006-- Soons 7	5/21/1964	235	7	29	8	0	14	21	154.4	6.3	88		0.1	41.050374	-74.223758
030014-- Bush 5	5/21/1964	338	7.7	44	11	0	16	25	213.3	9	144		0	41.023708	-74.250703
030005-- Camp Yah Paw	5/28/1964	203	7.2	32	3.2	0.2	2.5	18	125.0	4.9	100	0	1	41.087318	-74.229036
030007-- Camp Glen 3	7/8/1964	120	6.7	13	2.9	1	1.9	15	80.9	3.7	45	0	0.5	41.063985	-74.241258
030003-- Camp Tamar	7/17/1964	88	6.2	7.6	2.7	1	3.3	19	58.8	3.4	19	0	0.1	41.041763	-74.244869
030013-- Ford 1	8/25/1964	181	6.9	21	5.4	0.9	8.1	22	110.3	5.6	66	0	0	41.094485	-74.172728
030019-- Ford 4	8/25/1964	202	6.8	22	5.4	1	16	20	117.7	7.1	62	0	0	41.094902	-74.172701
310010-- Haskell	4/9/1969	207	7.6	23	6.2	0.5	5	26	132.4	6.8	82	0	0	41.03593	-74.284037
310009-- PW 5	4/9/1969	262	8	25	10	1.5	3.5	18	161.8	14	136	0	0.2	41.122318	-74.244592
310008-- PW 4	4/9/1969	229	7.3	28	5.7	0.5	11	25	154.4	5.2	82	0	0	41.089818	-74.264871
310012-- Crescent Pk 1	4/11/1969	229	7.1	21	7.5	0.5	3.5	25	132.4	9.7	95	0	0	41.104263	-74.400709
030094-- Bush 4	5/21/1982	330	7.4	41	8.7	0.8	25	23	228.0	8.5			0.3	41.024236	-74.252258
030006-- Soons 7	5/21/1982	377	6.6	45	10	0.8	40	23	257.4	9.8			0.1	41.050374	-74.223758
030184-- PW 9	5/21/1982	360	6.6	46	8.9	0.7	22	38	242.7	9.5			0.1	41.026153	-74.229813
030014-- Bush 5	5/21/1982	580	7.6	62	13	1.1	62	28	353.0	22			0.1	41.023708	-74.250703
030023-- PW 16	5/21/1982	225	8.5	25	6.5	0.7	18	20	139.7	5.1			0.1	41.085068	-74.183645
030019-- Ford 4	5/21/1982	263	7	21	4.8	0.7	44	19	176.5	18			0.1	41.094902	-74.172701
030013-- Ford 1	5/21/1982	200	7	16	3.9	0.6	35	16	139.7	11			0.1	41.094485	-74.172728
030009-- Soons 8	5/21/1982	240	6.7	30	6.3	0.5	16	18	154.4	7.3			0.1	41.050652	-74.224591
270028-- Green Pond 5 Obs	6/22/1983	266	8.2	35	12	0.5	4.9	22	176.5	3.3	140		0.1	41.035375	-74.449599
030009-- Soons 8	9/15/1983	240	7.7	33	6.5	0.7	20	18	154.4	7.3			0.1	41.050652	-74.224591

030182-- Soons 6	9/15/1983	320	6.6	35	9.2	0.9	44	21	205.9	14	84		0.1	41.050486	-74.225035
030006-- Soons 7	9/15/1983	332	7.3	44	9.7	0.9	31	22	205.9	9.7			0.1	41.050374	-74.223758
030006-- Soons 7	11/15/1983	342	7.1	44	10	0.8	35	21	220.6	11			0.2	41.050374	-74.223758
030182-- Soons 6	11/15/1983	312	6.8	32	9.2	0.9	42	21	205.9	14	79		0.2	41.050486	-74.225035
030009-- Soons 8	11/15/1983	265	8.3	35	6.8	0.6	23	18	169.2	7.7			0.1	41.050652	-74.224591
030009-- Soons 8	12/2/1983	235	8.3	29	5.7	0.6	18	17	147.1	6.4			0.1	41.050652	-74.224591
030182-- Soons 6	12/2/1983	327	6.7	33	8.9	0.9	41	21	205.9	14	70		0.1	41.050486	-74.225035
030006-- Soons 7	12/2/1983	356	7.1	42	9.3	0.8	34	21	213.3	11			0.1	41.050374	-74.223758
030263-- Cragmere E14	3/20/1984	498	7.2	49	22	1	40	27	301.5	14			0.1	41.096207	-74.125977
030236-- Camp Yaw Paw 2	4/4/1984	77	6.4	10	1.1	0.6	3.1	12	44.1	2.9			1.1	41.085652	-74.227091
030148-- Com 1	4/5/1984	163	8.6	22	3.4	0.7	6.8	18	95.6	4.8			0.2	41.099263	-74.163478
030189-- Irr	4/10/1984	279	7.6	38	7.8	0.6	18	16	169.2					41.003709	-74.242091
030146-- Ind 2	4/10/1984	505	7.7	56	25	0.6	37	30	308.9	9.7			0.1	41.102874	-74.149311
030147-- Ind 3	4/10/1984	500	7.8	59	23	0.8	39	26	301.5	10			0.1	41.101207	-74.1482
030028-- 4096	4/18/1984	270	8.1	27	12	0.5	17	24	191.2		10		0.1	41.055097	-74.183201
030023-- PW 16	4/18/1984	238	8.6	29	7.3	0.8	17	19	154.4	6.4			0.1	41.085068	-74.183645
030139-- Ford 2	4/18/1984	254	8.3	28	5.9	0.9	30	19	161.8	13			0.1	41.093429	-74.172673
030019-- Ford 4	4/18/1984	154	6.8	11	3.1	0.6	31	15	117.7	15			0.1	41.094902	-74.172701
030247-- Brookfield 1	4/19/1984	370	8	37	13	0.4	16	54	264.8	20			0.1	41.061402	-74.164395
030012-- Cent Av 1	4/19/1984	333	7.7	38	16	0.8	27	43	264.8	17			0.1	41.079818	-74.150978
030094-- Bush 4	4/25/1984	335	7.8	39	8.8	1	32	21	213.3	15			0.2	41.024236	-74.252258
030014-- Bush 5	4/25/1984	598	7.6	61	14	1.2	71	26	331.0	28			0.1	41.023708	-74.250703
030195-- Irr	4/26/1984	282	8.3	35	9.1	0.5	13	20	169.2	5.9			0.1	40.991486	-74.216535
030174-- Elbert St	5/1/1984	256	8.4	20	9.1	0.6	9.3	28	176.5	16			0.2	41.067596	-74.149588
030015-- Woodland Well	5/2/1984	304	7.3	31	11	0.8	17	26	228.0	11			0.1	41.054819	-74.164311
030017-- Drlngtn Well	5/2/1984	348	8.2	34	13	0.6	22	45	257.4	13			0.1	41.059597	-74.159089
030034-- Spring St	5/3/1984	378	7.8	32	15	0.8	23	34	242.7	20			0.3	41.074096	-74.142172
030184-- PW 9	5/7/1984	368	7.7	46	9.4	0.7	22	37	257.4	11			0.1	41.026153	-74.229813
030181-- Pine St 1	5/7/1984	560	6.7	56	15	1	82	25	389.8	25			0.1	41.027597	-74.247647
030187-- Rec 1	5/8/1984	251	6.9	20	6.8	0.7	32	18	161.8	17			0.1	41.020375	-74.25737
030142-- Fyke Rd 1	5/10/1984	468	8.5	31	13	0.2	5.9	120	301.5	40			0.2	41.059541	-74.193201

030058-- Dom	5/24/1984	290	7.8	37	6.8	1.1	34	15	220.6	7.1			1.6	41.034264	-74.250147
030180-- Rec 1	5/24/1984	380	7.3	45	12	0.8	31	22	250.1	10			0.1	41.015931	-74.256536
030191-- Rec 1	5/24/1984	500	7.2	55	17	1.1	44	24	367.7	14			0.2	41.016764	-74.259592
030246-- Darlington Racquet 1	5/24/1984	285	8.5	18	7.1	0.3	5.1	56	198.6	30			0.3	41.066485	-74.181812
030248-- Dom 1	5/25/1984	148	7.5	18	3.3	0.4	4	15	103.0	6.1			1.4	41.060374	-74.22848
030257-- Camp Glen Gray 2	5/25/1984	61	6.1	5.8	1.9	0.4	2.1	13	44.1	2.2			0.1	41.062319	-74.237369
030007-- Camp Glen 3	5/25/1984	134	7	18	2	0.6	2.1	14	95.6	4.5			0.9	41.063985	-74.241258
030242-- Dom 1	6/6/1984	144	7	13	4.5	0.4	7.2	15	110.3	4			0.1	41.013986	-74.225146
030240-- Dom 1	6/6/1984	350	6.8	38	13	0.5	20	27	257.4	8.8			0.1	41.017042	-74.230147
030237-- Dom 1	6/6/1984	204	8.5	21	8.3	0.4	3.3	33	154.4	11			0.1	41.071485	-74.160422
030238-- Dom 1	6/7/1984	260	8.3	27	9.3	0.7	20	19	183.9	4			0.1	41.045097	-74.175978
030068-- Dom	6/7/1984	518	8.1	50	13	0.9	66	28	316.3	27			0.1	41.081207	-74.179034
030003-- Camp Tamar	6/7/1984	78	6	5.9	2.6	0.7	2.6	19	44.1	2.4			0.1	41.041763	-74.244869
030077-- Dom	6/11/1984	171	8.2	18	4.9	0.3	2.7	19	132.4	11			0.1	41.053708	-74.21598
030059-- Dom	6/11/1984	180	8.2	18	4	0.4	2.4	19	132.4	12			0.1	41.066485	-74.205424
030162-- Dom	6/12/1984	294	8.2	20	9.2	0.6	9.9	30	176.5	21			0.1	41.044541	-74.178478
030053-- Dom	6/12/1984	80	6.1	6.6	1.9	0.6	3.3	16	66.2	3.8			0.1	41.064541	-74.21348
030066-- Dom	6/13/1984	191	7.4	23	5.8	0.5	5.5	24	139.7	7.2			0.1	41.078152	-74.182367
030005-- Camp Yah Paw	6/13/1984	190	7.8	31	2.2	0.5	2.1	22	125.0	4.5			1.5	41.087318	-74.229036
030038-- Franklin Lakes 1	6/14/1984	350	7.9	46	11	0.7	21	28	235.4	7.1			0.1	40.991764	-74.213201
030037-- Hilltop Ter TW	6/14/1984	380	7.8	48	9.3	0.8	28	26	250.1	10			0.1	40.996486	-74.236813
030261-- High Mtn Rd 1	6/14/1984	338	6.8	34	8.6	0.7	35	25	205.9	14			0.1	40.988987	-74.210423
030245-- Darlington Park 2	6/15/1984	339	8.3	30	14	0.4	14	44	250.1	15			0.1	41.062874	-74.176534
030153-- Dom	6/15/1984	444	7.8	47	19	0.5	15	31	279.5	15			0.1	41.062319	-74.176534
030253-- Dom 1	6/19/1984	360	8.2	35	14	0.3	41	18	242.7	11			0.1	41.010375	-74.222646
030050-- Dom	6/19/1984	150	8.6	19	1.9	< 0.10	2.3	17		9.7			0.8	41.065096	-74.21348
030252-- Dom 1	6/19/1984	251	8.2	35	7.2	0.7	5	37	169.2	4.4			0.1	41.069819	-74.161256
030161-- Dom	6/20/1984	358	7.4	35	8	0.7	49	18	250.1	17			0.1	41.060097	-74.210979
030250-- Com 1	6/21/1984	328	7.6	43	9.1	0.7	16	24	220.6	7.1			0.1	40.993709	-74.213479
030063-- Dom	6/21/1984	675	6.5	58	14	0.9	130	24	419.2	35			0.1	41.066485	-74.18209

030051-- Dom	6/27/1984	160	8.7	18	2.7	0.2	2.5	16	132.4	11			1.4	41.061208	-74.21848
030241-- Dom 1	6/27/1984	494	7.9			0.3	55	25						41.014542	-74.21459
030013-- Ford 1	6/27/1984	202	6.9			0.7	34	16					0.1	41.094485	-74.172728
030244-- Dom 1	6/28/1984	414	6.8			1	79	18	169.2					40.99982	-74.232369
030251-- Dom 1	6/28/1984	102	6.4			0.5	8.4	17						41.067319	-74.212646
030243-- Dom 1	6/29/1984	400	6.8			0.9	56	26						41.003431	-74.229591
030254-- Dom 1	6/29/1984	282	8.1			0.3	18	23						41.007597	-74.227368
270028-- Green Pond 5 Obs	12/30/1985	276	8.4	37	13	0.5	6.7	16	147.1	3.3	135		0.1	41.035375	-74.449599
030034-- Spring St	3/11/1986	458	7.7	40	20	0.8	41	38	257.4	22				41.074096	-74.142172
270055-- Indian Lane 1	8/13/1987	357	8.2	51	14	0.8	14	55	242.7	9.8	160		0.1	40.935015	-74.34365
271113-- Indian Lane 3/Montvi 6	8/13/1987	436	8.2	63	16	1.1	18	94	286.8					40.935654	-74.33765
271114-- BOE	8/17/1987	260	8.2	24	15	0.5	13	20	161.8	9.7	118		0.1	40.916765	-74.340984
310016-- Lincoln Ave 2	8/19/1987	268	8.4	29	3.2	1	11	32	169.2	27	121		0.6	40.981014	-74.283509
270922-- Main Supply 1	8/19/1987	370	8.2	52	14	1.2	15	50	235.4	13	155		0.1	40.991487	-74.297927
271115-- PW 2	8/28/1987	264	8.2	37	11	0.7	11	25	169.2	5.5	123		0.1	40.978987	-74.308205
030034-- Spring St	3/2/1988	493	7.4	43	21	1	48	34	272.1	23	148		0.3	41.074096	-74.142172
310055-- Awosting 3 - Wm 3040	8/25/1989	236	7.3	22	11	0.5	21	11	139.7	8.6	79	<.1	0.7	41.152595	-74.338485
310054-- 1 Of 3	8/25/1989	216	6.4	22	7.8	0.6	24	16	139.7	8.8	56	<0.1	0.2	41.09593	-74.379597
310057-- Concord Rd-Bald Eagle	9/26/1989	422	7.5	47	16	0.5	32	29	228.0	16	172	<.1	0.1	41.11093	-74.39182
310009-- PW 5	9/26/1989	350	7.4	49	10	0.7	26	11	183.9	7.5			0.1	41.122318	-74.244592
030236-- Camp Yaw Paw 2	9/28/1989	74	6.5	12	1.1	0.6	1.2	10	51.5	3.2	33		1.1	41.085652	-74.227091
310058-- Institutional 1	9/11/1990	274	7	39	7.7	1	13	24	176.5	5.6	126	103	0.2	41.093707	-74.265148
310060-- PW 4	9/12/1990	176	7.3	15	5.6	0.6	9.9	12	103.0	7.8	74	61	1.3	41.159262	-74.328762
030182-- Soons 6	6/16/1993	452	6.9	48	11	1.2	63	19	286.8	23	105	86	0.1	41.050486	-74.225035
310010-- Haskell	6/17/1993	344	7.5	43	10	1	17	33	191.2	11			0.1	41.03593	-74.284037
310064-- Beattie Ln9	6/24/1993		6.3	12	4.5	1.1	30	16	103.0	15	30		0.1	41.068985	-74.282927
310067-- Du-147A	9/21/1993	318	6.2	33	8	3.5	50	33	191.2	9.1			0.1	40.970376	-74.278759
310062-- Dc114A	9/21/1993	473	6.6	41	11	1.5	30	13	264.8	35			0.3	40.971765	-74.279593

310063-- Dc147	9/21/1993	1090	7.3	110	43	1	19	470	764.9	68			0.2	40.970376	-74.278759
310061-- Dc114	9/21/1993	2360	9.3	170	49	1.1	39	1200	1853.4	330			0.4	40.971765	-74.279593
310067-- Du-147A	8/9/1995	300	6.1	29	7.3	2.8	39	37	176.5	10	37	30	0.1	40.970376	-74.278759
310144-- SUS 0107 Dom	8/26/1997	798	7.9	98.5	23.4	1.86	106	36.8	536.9	12.4			0.1	41.092444	-74.257833
310143-- SUS 0122 Dom	8/27/1997	571	7.3	58.3	23.5	0.76	94.4	14.4	404.5	6.27			0.12	41.08475	-74.373667
310142-- SUS 0139 Dom	9/16/1997	100	5.9	8.64	3.6	0.57	4.31	10.2	73.5	5.45			0.1	41.067389	-74.326111
310141-- SUS 0136 Dom	9/16/1997	428	6.7	30	15.2	0.87	69	28.2	220.6	18.2			0.1	41.055417	-74.459611
310146-- SUS 0080 Dom	11/2/1997	317	7.6	35.6	9.6	0.72	1.86	7.09	191.2	20.6			0.59	41.129444	-74.3585
310016-- Lincoln Ave 2	11/3/1997	341	8.3	40.1	4.34	1.21	19.4	35.1	191.2	23.9			0.51	40.981014	-74.283509
310147-- SUS 0253 Dom	11/9/1997	365	7.4	40	13.2	0.6	58.1	8.46	235.4	5.76			0.1	41.034889	-74.392833
030238-- Dom 1	9/5/2001	289	8.2	30.8	10.7	0.77	18.8	17.7		4.81			0.2	41.045097	-74.175978
030253-- Dom 1	9/5/2001	830	7.8	70.3	27.2	0.51	159	14.8		26.1			0.2	41.010375	-74.222646
030053-- Dom	12/17/2001	147	5.7	10.9	3.4	0.79	17.6	11.1	88.3	9.17			0.16	41.064541	-74.21348
310184-- MW81	11/20/2002	206	7	18.8	7.77	3.48	11.6	12.3	125.0	6.84	65		0.17	41.037319	-74.345429
310200-- MW137	3/24/2004	1510	6.7	137	63.5	1.14	164	15.8	801.7	47.5	618		0.31	40.960833	-74.278333
310184-- MW81	4/18/2007	179	7.3	10.1	3.95	18.9	3.4	8.89	117.7	9.18	76		0.18	41.037319	-74.345429
310143-- SUS 0122 Dom	8/6/2007	844	7.2	90.4	35.1	1.02	179	17.8		8.3				41.08475	-74.373667
310177-- Institutional 10	8/27/2007	725	7.5	81.6			137	23.4						41.114263	-74.368486
310169-- Institutional 2	8/27/2007	260	7.7	31			5.93	6.55						41.131485	-74.360152
310166-- Institutional 1	8/28/2007	161	6.8	12			16.9	6.58						41.058986	-74.4646
310184-- MW81	6/20/2012	68	5.9	4.45	1.49	4.43	1.48	8.99		4.65	25			41.037319	-74.345429
310200-- MW137	4/18/2016	1120	6.8	117	46.3	1.32	154	22.2		43.6	361		0.15	40.960833	-74.278333

Appendix 3. All Middle Passaic River Basin mean, data count, max, min, and standard deviation.

1960s	Specific Conductance (uS/cm)	pH	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Cl (mg/L)	SO_4 (mg/L)	TDS (mg/L)	Na (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	F (mg/L)
Mean	229.18	7.32	25.92	7.43	0.46	8.81	22.88	144.93	7.99	91.82	0	0.12
Count	17	17	17	17	17	17	17	17	17	17	12	17
Max	364	8.1	44	16	1.5	25	39	228.00	16	144	0	1
Min	88	6.2	7.6	2.7	0	1.9	15	58.84	3.4	19	0	0
SD	-	-	8.55	3.47	0.47	6.09	5.45	42.79	3.98	33.59	0	0.26
1980s	Specific Conductance (uS/cm)	pH	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Cl (mg/L)	SO_4 (mg/L)	TDS (mg/L)	Na (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	F (mg/L)
Mean	307.87	7.57	33.74	9.70	0.68	25.27	26.02	198.58	12.15	105.19	-	0.24
Count	92	92	86	86	91	92	92	86	83	16	-	84
Max	675	8.7	63	25	1.2	130	120	419.22	40	172	-	1.6
Min	61	6	5.8	1.1	0.2	1.2	10	44.13	2.2	10	-	0.1
SD	-	-	13.93	5.25	0.24	21.29	15.63	76.77	7.55	47.86	-	0.35
1990s	Specific Conductance (uS/cm)	pH	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Cl (mg/L)	SO_4 (mg/L)	TDS (mg/L)	Na (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	F (mg/L)
Mean	544.19	7.15	50.07	14.70	1.26	39.00	117.49	353.02	35.71	74.40	70.00	0.27
Count	16	17	17	17	17	17	17	17	17	5	4	17
Max	2360	9.3	170	49	3.5	106	1200	1853.38	330	126	103	1.3
Min	100	5.9	8.64	3.6	0.57	1.86	7.09	73.55	5.45	30	30	0.1
SD	-	-	40.77	13.17	0.79	30.68	299.49	423.59	77.38	41.74	31.76	0.31
2000s	Specific Conductance (uS/cm)	pH	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Cl (mg/L)	SO_4 (mg/L)	TDS (mg/L)	Na (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	F (mg/L)
Mean	515.10	7.19	49.29	21.66	3.80	71.32	13.49	286.83	15.99	253.00	-	0.20
Count	10	10	10	7	7	10	10	4	7	3	-	6
Max	1510	8.2	137	63.5	18.9	179	23.4	801.66	47.5	618	-	0.31
Min	147	5.7	10.1	3.4	0.51	3.4	6.55	88.26	4.81	65	-	0.16
SD	-	-	45.84	21.61	5.61	75.79	6.08	287.71	16.39	232.86	-	0.05

Appendix 4. Hydraulic Head data collected from the USGS for the Lower Passaic River Basin

SiteName	Field Measurement Date	Land Surface Elevation Above NGVD29 (ft)	Well Depth Below Land Surface (ft)	Water Depth Below Land Surface (ft)	Hydraulic Head (ft)	Latitude	Longitude
130016-- Ind 1	7/1/1960	15	500	30	-15	40.7314905	-74.132921
310005-- Utter Ave	10/3/1960	150	300	43	107	40.96134805	-74.1453379
130089-- Cooling-1	11/5/1960	240	400	53	187	40.81121125	-74.2026454
030239-- PW 6	6/24/1961	240	300	30	210	41.015375	-74.1329209
030249-- Fardale 1	6/27/1961	400	320	30	370	41.03870799	-74.1634777
310006-- Goffle Hill	2/15/1962	255	350	62	193	40.97090345	-74.1621718
030143-- Fyke Rd 2	5/15/1962	445	125	5	440	41.05370775	-74.1907009
170006-- Ind 1	10/16/1962	70	400	135	-65	40.77065646	-74.13903238
030255-- DPW-Crescent Dr	1/1/1964	450	440	37	413	41.068152	-74.1209765
030173-- Dixon St	3/26/1965	379	400	3	376	41.0578188	-74.1286988
030235-- Dom 1	9/12/1965	550	215	30	520	41.09287387	-74.1212545
030350-- Meeker Lane TW 17	10/4/1965	350	120	10	340	41.04315238	-74.1320877
030268-- Home Pl-TW 2	11/6/1965	20	450	1	19	40.87148838	-74.0893084
030275-- Irr 1	1/13/1966	40	55	7	33	40.80815595	-74.1223651
030276-- Rec 1	1/22/1966	55	122	31	24	40.8062115	-74.1223652
030175-- Rec 1	3/28/1966	358	348	30	328	41.0500967	-74.13181
030223-- PW 3	5/19/1966	266	300	24	242	41.02059717	-74.12575399
030299-- Dull Field	8/16/1966	90	400	33	57	40.8484609	-74.1005866
310053-- Ac 3	8/20/1966	255	342	23	232	40.9481537	-74.2307019
030264-- Ind 3	12/12/1968	45	300	20	25	40.8573219	-74.1001421
310007-- Ind 1	3/20/1969	12	500			40.855933	-74.1112536
130091-- 2-Irrigation Pond	5/4/1971	185	335	1	184	40.84259976	-74.17347779
030227-- Ind 3	9/15/1971	15	470	12	3	40.8453776	-74.1187539
310033-- Arlington Ave 3	5/19/1975	80	408	46	34	40.8798215	-74.1384766
130088-- Standby	8/9/1976	105	354	6	99	40.7728785	-74.1857004
310034-- 3-Irrigation	4/21/1980	180	300	-2	182	40.8464886	-74.1704221
030273-- Dom 1	1/25/1981	110	180	48	62	40.86565516	-74.0745857
030274-- Dom 1	3/12/1981	80	118	29	51	40.86871067	-74.0745857
130087-- 3-1981	5/21/1981	20	165	30	-10	40.7312127	-74.13597668
030265-- Com 1	11/1/1981	80	200	17	63	40.8423221	-74.1034756

030271-- Dom 1	11/20/1981	100	150	41	59	40.8681551	-74.0726412
030466-- Hollywood Ave OW 6	7/1/1983	125	300	15.5	109.5	41.00259744	-74.10791988
030262-- Fardale 2	3/20/1984	310	300			41.03287475	-74.15319948
030301-- PW 2	3/28/1984	231	256			41.01284728	-74.1288929
030259-- Orchard St 1	5/10/1984	326	303			41.04890229	-74.14761609
030159-- Dom	6/6/1984	380	130			41.0331525	-74.1723668
030260-- ShadOW Lks 2	6/14/1984	350	92			41.03148587	-74.190423
030258-- E Oak St 1	6/19/1984	335	297			41.0477356	-74.1498662
310036-- 1-Clbhse	8/21/1985	185	491			40.848433	-74.1726444
030232-- 1-Clubhouse	1986	70	306	13	57	40.94620945	-74.0768078
030285-- Aquaculture 1	1/15/1986	10	188	42	-32	40.85843298	-74.1143092
310035-- Tower 2	3/11/1986	290	561			40.94870927	-74.2337575
030233-- Ind 3	3/12/1986	50	325			40.90426559	-74.1290319
310065-- Dc-122	5/21/1993	160	273	5	155	40.8959322	-74.2665364
310066-- Du-122A	12/1/1993	160	28	7.6	152.4	40.8959322	-74.2665364
030477-- Central Ave 1	11/3/1997	350	247			41.0648187	-74.1459773
030418-- PW 10	11/5/1997	50	350			40.91426546	-74.1148647
030419-- PW 12	11/5/1997	50	350			40.9112099	-74.12180939
030724-- MW146	10/9/2003	299	36	6	293	41.0383333	-74.11388889
030723-- MW149	10/10/2003	72	38	9	63	40.9286111	-74.0691667
130192-- MW141	10/16/2003	206	20	13	193	40.8633333	-74.2266667
310199-- MW142	10/17/2003	233	22	11	222	40.9422222	-74.2216667
310198-- MW145	10/19/2003	30	22	13	17	40.9097222	-74.13388889
130193-- MW144	1/22/2004	12	8.3	4.3	7.7	40.8123225	-74.13986568
030724-- MW146	4/29/2008	299	36	9.6	289.4	41.0383333	-74.11388889
310199-- MW142	4/30/2008	233	22	9	224	40.9422222	-74.2216667
310198-- MW145	7/7/2008	30	22	12.8	17.2	40.9097222	-74.13388889
130193-- MW144	7/16/2008	12	8.3	2.15	9.85	40.8123225	-74.13986568
030723-- MW149	7/16/2008	72	38	12.5	59.5	40.9286111	-74.0691667
130192-- MW141	7/23/2008	206	20	12	194	40.8633333	-74.2266667
030723-- MW149	4/16/2013	72	38	16.5	55.5	40.9286111	-74.0691667
310199-- MW142	6/11/2013	233	22	9.73	223.27	40.9422222	-74.2216667
130192-- MW141	6/25/2013	206	20	10.28	195.72	40.8633333	-74.2266667
310199-- MW142	4/25/2016	233	22	10.18	222.82	40.9422222	-74.2216667

030723-- MW149	6/28/2016	72	38	14.95	57.05	40.9286111	-74.0691667
310198-- MW145	7/6/2016	30	22	11.45	18.55	40.9097222	-74.13388889
130192-- MW141	7/25/2016	206	20	17.1	188.9	40.8633333	-74.2266667
030724-- MW146	8/17/2016	299	36	14.06	284.94	41.0383333	-74.11388889

Appendix 5. Groundwater quality measurements collected from the USGS for the Lower Passaic River Basin.

Sitenames	Sample Date	Specific Conductance (μ/cm)	pH	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Cl (mg/L)	SO_4 (mg/L)	TDS (mg/L)	Na (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	F (mg/L)	Latitude	Longitude
030008-- PW 4	4/29/1959	384	8.2				16	63			166	1		40.9967642	-74.10958659
030011-- PW 1	4/29/1959	307	8.4				8.4	78			128	2		41.017875	-74.1293096
030016-- Martis Ave	4/29/1959	198	8.1				3.6	15			105	0		41.0456523	-74.1570886
130016-- Ind 1	5/10/1961			542	133		1140	414						40.7314905	-74.132921
130016-- Ind 1	5/2/1968	5100	7.9	620	185	7.5	1400	517	4883.5	145			0.1	40.7314905	-74.132921
310007-- Ind 1	3/20/1969	787	7.8	82	26	2.3	54	74	507.5	24	260	0	0	40.855933	-74.1112536
310005-- Utter Ave	4/2/1969	8.1	3.8	12	0.8	16	39	0.34		9	136	0	0	40.9613481	-74.1453379
310006-- Goffle Hill	4/2/1969	405	8.2	35	18	1.2	23	27	242.7	10	157	0	0	40.9709035	-74.1621718
310004-- Main Field 5	4/2/1969	521	8.1	50	19	2	40	34	316.3	15	183	0	0	40.9578759	-74.1554216
310001-- Ac 1	6/5/1969	823	8.4	80	34	3	51	150	566.3	36	246	4	0	40.8245446	-74.12514298
030262-- Fardale 2	3/20/1984	290	6.5	32	8.6	1.3	23	29	176.5	10			<0.1	41.0328748	-74.15319948
030249-- Fardale 1	3/20/1984	576	6.8	56	18	1	54	53	345.7	25			<0.1	41.038708	-74.163478
030239-- PW 6	3/28/1984	412	7.9	34	23	1.2	34	32	242.7	12			0.1	41.015375	-74.1329209
030223-- PW 3	3/28/1984	460	7.9	41	23	1.2	42	22	264.8	12			<0.1	41.0205972	-74.12575399
030301-- PW 2	3/28/1984	1060	7.8	78	44	1.6	230	37	610.4	54			<0.1	41.0128473	-74.1288929
030016-- Martis Ave	4/19/1984	255	8.2	21	14	0.8	9.8	23	176.5	15			0.2	41.0456523	-74.1570886
030256-- Wd-Crescent Dr	4/19/1984	254	8.2	24	16	0.6	14	30	213.3	14			0.2	41.0707075	-74.120032
030175-- Rec 1	4/25/1984	212	8.4	14	12	0.7	7.2	13	132.4	12			0.3	41.0500967	-74.13181
030143-- Fyke Rd 2	4/26/1984	236	8.4	22	11	0.3	4.7	21	183.9	11			0.1	41.0537078	-74.1907009
030173-- Dixon St	5/1/1984	360	7.8	42	12	1	22	32	264.8	9			0.3	41.0578188	-74.1286988
030255-- DPW-Crescent Dr	5/3/1984	446	7.7	43	22	1	32	34	279.5	9			0.2	41.068152	-74.1209765
030259-- Orchard St 1	5/10/1984	393	8.1	32	17	0.9	19	33	235.4	18			0.1	41.0489023	-74.14761609
030159-- Dom	6/6/1984	365	8	36	17	0.8	16	41	250.1	8.1			<0.1	41.0331525	-74.1723668
030036-- Franklin Lakes 1957	6/14/1984	445	7.4	56	9.3	1.1	34	34	286.8	16			0.1	41.0317636	-74.1893118
030260-- ShadOW Lks 2	6/14/1984	402	7.1	45	8.6	1.2	43	20	272.1	17			<0.1	41.0314859	-74.190423
030258-- E Oak St 1	6/19/1984	303	7.5	29	9.5	0.7	24	24	191.2	12			0.1	41.0477356	-74.1498662
030235-- Dom 1	6/28/1984	325	8.2			0.8	10	27						41.0928739	-74.1212545
030230-- Ames 3	3/6/1986	550	7.6	44	33	1.2	49	27	294.2	16				41.0064029	-74.1808391
130089-- Cooling-1	8/19/1987	635	7.2	66	26	2.9	74	64	360.4	21	166	<0.1	0.1	40.8112113	-74.2026454

310053-- Ac 3	9/3/1987	286	8.1	35	12	0.8	14	45	198.6	10	102		0.1	40.9481537	-74.2307019
310035-- Tower 2	9/14/1987	385	7.6	41	15	0.8	16	60	235.4	12	106	<0.1	0.2	40.9487093	-74.2337575
030230-- Ames 3	3/7/1988	588	7.1	45	34	1.3	53	22	308.9	18	206	<0.1	0.1	41.0064029	-74.1808391
030228-- E Saddle River	5/4/1988	479	7.9	52	19	1	37	25	286.8	20	206	<0.1	0.1	40.9877921	-74.08844699
030267-- Columbia Ave	8/12/1988	550	7.3	88	14	1.1	37	100		8.6			<0.1	40.878155	-74.0698633
030268-- Home Pl-TW 2	8/16/1988	480	7.8	33	26	1	24	64	272.1	22			<0.1	40.8714884	-74.0893084
310033-- Arlington Ave 3	8/19/1988	634	7.5	63	33	1.2	60	90	404.5	23	162	<0.1	<0.1	40.8798215	-74.1384766
310034-- 3-Irrigation	8/19/1988	477	6.9	54	16	0.8	56	32	316.3	14	132	<0.1	<0.1	40.8464886	-74.1704221
030232-- 1-Clubhouse	9/12/1988	436	7.3	56	17	0.9	17	35		10			<0.1	40.946209	-74.076808
030264-- Ind 3	1/11/1989	552	8.1	50	28	1.4	49	34	323.6	24			<0.1	40.8573219	-74.1001421
030265-- Com 1	1/11/1989	797	7.3	99	28	1.8	87	59	500.1	32			0.2	40.8423221	-74.1034756
030274-- Dom 1	8/22/1989	484	7.7	72	15	1.1	44	31	308.9	13			0.1	40.8687107	-74.0745857
030271-- Dom 1	8/23/1989	578	7	87	9.7	1.2	69	25	345.7	16			<0.1	40.8681551	-74.0726412
030276-- Rec 1	8/24/1989	520	7.6	65	17	2.7	59	33	316.3	12			0.1	40.8062115	-74.1223652
030273-- Dom 1	8/24/1989	451	7.6	64	13	1.4	43	14	272.1	8.3			0.1	40.865655	-74.074586
030275-- Irr 1	8/24/1989	711	7.5	77	19	2.2	60	36	345.7	14			0.1	40.808156	-74.1223651
030285-- Aquaculture 1	8/29/1989	596	7.7	69	22	1.4	43	82	367.7	25			0.1	40.858433	-74.1143092
030287-- Wallington 1 Obs	7/17/1990	760	7.2	110	12	1.9	90	38	478.1	42			0.2	40.8517664	-74.0987532
030286-- Wallington 2 Obs	7/19/1990	721	7.5	89	18	1.5	72	34	419.2	29			0.2	40.8481554	-74.1006977
030299-- Dull Field	7/19/1990	643	7.4	82	22	1.5	69	33	404.5	25			0.2	40.8484609	-74.1005866
030288-- Wallington 3 Obs	1/15/1991	529	7.8	79	12	1	37	38	345.7	13			< 0.1	40.8520442	-74.1020867
310065-- Dc-122	12/1/1993	1850	8.1	250	58	1.9	28	1000	1647.5	110			0.2	40.8959322	-74.2665364
310066-- Du-122A	12/1/1993	505	6.2	28	8.2	4.3	70	59	294.2	53			0.1	40.8959322	-74.2665364
030477-- Central Ave 1	11/3/1997	546	7.5	52.5	21.9	1.06	64.2	40.2	308.9	23.2			0.1	41.0648187	-74.1459773
030460-- Mem Park 15	11/3/1997	731	6.9	97.7	16.6	4.28	74	29.8	411.9	29.5			<0.1	40.928154	-74.137921
030301-- PW 2	11/5/1997	2510	7.5	135	72.7	2.46	738	31.1	1338.6	238			<0.1	41.0128473	-74.1288929
030419-- PW 12	11/5/1997	711	7.7	78.6	27.3	1.24	62	94.6	411.9	17.7			<0.1	40.9112099	-74.12180939
030418-- PW 10	11/5/1997	697	7.5	73.8	23.8	1.61	74.9	41.8	382.4	24.4			<0.1	40.9142655	-74.1148647
030301-- PW 2	9/22/1999	2250	7.7	115	61.6	2.01	634	31.5		209			<0.1	41.0128473	-74.1288929

030460-- Mem Park 15	9/22/1999	697	7.3	79.2	17.7	3.87	74	32.1		28.8			<0.1	40.9281541	-74.137921
030273-- Dom 1	8/23/2001	544	7.7	66.2	14.2	1.32	79.2	14.1	308.9	8.39			0.2	40.8656552	-74.0745857
030159-- Dom	3/21/2002	513	7.5	50.4	22.6	1.02	40.4	35.1	294.2	13			<0.1	41.0331525	-74.1723668
030724-- MW146	3/9/2004	1100	6.2	64.2	22.4	1.78	269	37.9	639.9	121	104		0.17	41.0383333	-74.11388889
310198-- MW145	3/17/2004	1100	6.7	105	13.3	2.59	171	33.5	639.9	85.2	321		0.17	40.9097222	-74.13388889
030723-- MW149	3/23/2004	3500	7.2	210	37.4	2.42	944	49.4	2206.4	454	294		<.17	40.9286111	-74.0691667
310199-- MW142	3/25/2004	341	6.7	40.6	10.6	0.75	30.5	39.8	235.4	12.6	90		<0.17	40.942222	-74.221667
130192-- MW141	4/27/2004	1400	6.8	106	20.8	8.87	184	3.63	853.1	148	573		0.2	40.8633333	-74.2266667
130193-- MW144	4/28/2004	813	7.2	86.3	23.6	6.21	99.9	25.3	478.1	42	263		<0.1	40.8123225	-74.13986568
030724-- MW146	4/29/2008	1380	5.8	83.9	33.1	2.28	348	48.5	926.7	127	65		0.08	41.0383333	-74.11388889
310199-- MW142	4/30/2008	445	6.8	50	12.3	0.8	53.7	30.9	286.8	16.4	112		0.07	40.9422222	-74.2216667
310198-- MW145	7/7/2008	791	6.3	79.6	14.7	1.77	93.1	39.4	456.0	57	254		0.07	40.9097222	-74.13388889
030723-- MW149	7/16/2008	5410	7.1	233	40.6	2.48	1580	63.7	3530.3	779	303		<.12	40.9286111	-74.0691667
130193-- MW144	7/16/2008	831	6.8	74.7	20.3	6.45	100	24.8	478.1	58.1	288		<0.1	40.8123225	-74.13986568
130192-- MW141	7/23/2008	1270	7.5	120	32.7	3.26	266	29.7	698.7	74.1	204		0.1	40.8633333	-74.2266667
310198-- MW145	4/10/2013	1810	6.5	188	25	3.07	403	68.6		157	166		0.04	40.9281541	-74.137921
030723-- MW149	4/16/2013	4080	7	161	23.9	1.86	1120	51.3		607	338		0.04	40.9422222	-74.2216667
310199-- MW142	6/11/2013	563	6.6	57.9	14.8	1.06	87.3	26.1		28.6	138		0.04	40.9462095	-74.0768078
030724-- MW146	6/19/2013	1160	5.9	30	10.9	1.54	279	49.4		177	123		0.08	41.038708	-74.1634777
130192-- MW141	6/25/2013	1570	7.3	140	36.7	3.25	345	24.4		96			0.04	40.8656552	-74.0745857
310199-- MW142	4/25/2016	692	6.7	68.7	17.1	1.11	134	27.1		46.6	130		0.04	40.942222	-74.221667
030723-- MW149	6/28/2016	2730	6.9	118	20.2	1.76	593	50.2		392	353		0.05	40.928611	-74.069167
310198-- MW145	7/6/2016	2700	6.7	248	29.1	3.81	697	36.9		219	197		0.04	40.909722	-74.133889
130192-- MW141	7/25/2016	1450	7.5	132	36.9	3.27	326	23.2		118	235		0.04	40.863333	-74.226667
030724-- MW146	8/17/2018	1920	6.6	112	37.4	2.82	455	60		246	277		0.07	41.038333	-74.113889

Appendix 6. All Lower Passaic River Basin mean, data count, max, min, and standard deviation.

1960s	Specific Conductance (uS/cm)	pH	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Cl (mg/L)	SO_4 (mg/L)	TDS (mg/L)	Na (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	F (mg/L)
Mean	429.14	7.63	51.80	19.56	4.90	29.38	55.17	411.86	18.80	172.63	0.88	0
Count	8	8	5	5	5	8	8	4	5	8	8	5
Max	823	8.40	82	34	16	54	150	566.31	36	260	4	0
Min	8.10	3.84	12.00	0.80	1.20	3.60	0.34	242.70	9	105	0	0
SD	-	-	29.90	12.30	6.24	19.29	47.50	153.51	11.30	55.19	1	0

1980s	Specific Conductance (uS/cm)	pH	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Cl (mg/L)	SO_4 (mg/L)	TDS (mg/L)	Na (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	F (mg/L)
Mean	472.77	7.64	50.26	18.96	1.19	42.65	38.51	286.83	16.56	154.29	-	0.14
Count	35	35	34	34	35	35	35	33	34	7	-	21
Max	1060.00	8.40	99	44	2.90	230	100	610.44	54	206	-	0.30
Min	212.00	6.50	14	8.60	0.30	4.70	13	132.38	8.10	102	-	0.10
SD	-	-	20.98	8.53	0.54	38.66	21.06	93.79	8.77	43.03	-	0.09

1990s	Specific Conductance (uS/cm)	pH	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Cl (mg/L)	SO_4 (mg/L)	TDS (mg/L)	Na (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	F (mg/L)
Mean	1011.54	7.41	97.68	28.60	2.20	160.55	115.62	588.37	64.82	-	-	0.17
Count	13	13	13	13	13	13	13	11	13	-	-	6
Max	2510	8.10	250	72.70	4.30	738	1000	1647.45	238	-	-	0.20
Min	505	6.20	28	8.20	1	28	29.80	294.19	13	-	-	0.10
SD	-	-	53.14	21.12	1.18	234.72	266.30	471.50	74.81	-	-	0.09

2000s	Specific Conductance (uS/cm)	pH	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Cl (mg/L)	SO_4 (mg/L)	TDS (mg/L)	Na (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	F (mg/L)
Mean	1388.43	6.88	97.85	22.76	3.00	304.20	33.98	860.50	142.56	239.25	-	0.13
Count	14	14	14	14	14	14	14	14	14	12	-	8
Max	5410	7.70	233	40.60	8.87	1580	63.70	3530.25	779	573	-	0.20
Min	341	5.8	40.6	10.6	0.75	30.5	3.63	235.35	8.39	65	-	0.07
SD	-	-	57.25	9.74	2.44	434.98	14.98	914.33	215.36	140.34	-	0.08

2010s	Specific Conductance (uS/cm)	pH	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Cl (mg/L)	SO_4 (mg/L)	TDS (mg/L)	Na (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	F (mg/L)
Mean	1867.50	6.77	125.56	25.20	2.36	443.93	41.72	-	208.72	217.44	-	0.05
Count	10	10	10	10	10	10	10	-	10	9	-	10
Max	4080	7.50	248	37.40	3.81	1120	68.60	-	607	353	-	0.08
Min	563	5.90	30	10.90	1.06	87.30	23.20	-	28.60	123	-	0.04
SD	-	-	64.62	9.65	1.00	301.71	16.34	-	175.45	88.53	-	0.01