CEE 6440 Term Project Paper

Using GIS to Map Chromium Occurrence in Drinking Water

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Introduction

Chromium in drinking water and its effects on human health have been a topic of concern for many years, but have been especially discussed over the last few decades. This concern was elevated beginning in 1991 when the U.S. Environmental Protection Agency (EPA) set an enforceable maximum contaminant level (MCL) of 100 parts per billion (ppb) due to concerns at the time that excessive consumption of chromium-contaminated water could lead to skin reactions (USEPA, 2013).

The two oxidation states of chromium found in drinking water are trivalent (Cr(III)) and hexavalent (Cr(VI)). An intriguing aspect of chromium chemistry is that one oxidation state is known to be a trace nutrient while the other is a probable carcinogen. The Cr(III) oxidation state is a known trace nutrient, often contained in daily human health supplements. On the other hand, Cr(VI) is a known carcinogen when inhaled and a suspected carcinogen when ingested (USEPA, 2010). These oxidation states can reduce or oxidize to one another in treatment and distribution systems, which is the main driving force to understand the oxidation kinetics of chromium in drinking water systems.

Sources of chromium in drinking water come from both naturally occurring and anthropogenic sources. Depending on geographic regions, natural chromium levels vary, as chromium is the 21st most common metal found in the earth's crust (Nriagu and Nieboer, 1988). There are also many mechanical and industrial processes that can lead to discharges into source water, such as leather tanning, wood preservation, and decorative chrome plating. Another potential source of chromium in drinking water is chromium contamination in drinking water treatment chemicals such as iron coagulants (Olsen, 2014).

There are currently no federal regulations on the carcinogenic oxidation state, Cr(VI), in drinking water, only for total chromium (TotCr), which is the combination of both Cr(III) and Cr(VI). As stated before, the MCL for TotCr is currently 100 ppb (USEPA, 2013). It is important to note that the MCL for chromium is measured at the entry point of the distribution system, which occurs at the end of the treatment process. Since both oxidation and reduction of chromium can occur in distribution system pipes, the concentration of Cr(VI) actually present at consumers' taps may differ from the entry point. There has been discussion of possible federal regulation of Cr(VI) for many years. The State of California set a revised MCL for TotCr at 50 ppb and was the first to create a regulation specifically for Cr(VI). Setting a possible example for federal regulation, the California Cr(VI) MCL was set at 10 ppb and began to be enforced in July 2014.

This project is an effort to use data from the third Unregulated Contaminant Monitoring Rule (UCMR3) provided by the Environmental Protection Agency (EPA) to map chromium occurrence in the United States (USEPA, 2015). Mapping the occurrence of chromium contamination in drinking water throughout the United States will provide a graphical aid in understanding how many people are currently affected by chromium contamination in drinking water. These maps will aid in the understanding of whether or not it would be beneficial to implement federal regulation specifically on Cr(VI).

It is important to remember that when discussing federal regulation of drinking water, one of the many considerations taken into account is economic feasibility. While it may be ideal to set a regulation well below the concentration thought to cause health effects, it may not be cost effective if the resulting chromium treatment is too expensive for consumers.

Objectives

The overall objective of this project is to use ArcGIS software and the UCMR3 data as well as population data to map the occurrence of both TotCr and Cr(VI) across the Untied States and how many people are being affected by these concentrations. With this data being graphically represented, it will effectively show how many regions would need additional treatment for drinking water to meet more stringent (possible) regulations. With the help of the ArcGIS software, population densities will also be known throughout each region of interest.

Data

The majority of the data that was used for this project was provided in the UCMR3 data. In 1996 there were a series of amendments made to the Safe Drinking Water Act (SDWA). One of these amendments required the EPA to issue a list of less than 30 previously unregulated contaminants to all public water systems (PWS's) every five years. This amendment became known as the unregulated contaminant monitoring rule. The third unregulated contaminant monitoring rule (UCMR3) includes 30 contaminants and went into effect on January 1, 2013 and will run until December 31, 2015. UCMR3 requires that any PWS serving more than 10,000 people must routinely monitor for each of the contaminants over the two-year period. All of the data from the routine monitoring of the PWS's is available online on the EPA website (USEPA, 2015).

Since the UCMR3 raw data includes all the data from each of the 30 contaminants, there is a lot data that is not needed for this project. As such, before any data was loaded into ArcGIS, the programming software R was used to filter out all the raw data to only include the data for chromium species. Included in the UCMR3 data are minimum, maximum and average values for both TotCr and Cr(VI) (USEPA, 2015). The R code that was used can be seen in the appendix.

While the UCMR3 data provided all the chromium data for each of the required PWS's that would be needed for the mapping, there was no longitude or latitude data connected to the location of the PWS's. Rather, the UCMR3 data provided zip codes that the PWS's served. This was both a benefit to this project as well as a challenge. The benefit of using zip codes was in the simplicity of finding population data for zip codes and then linking the population data to the UCMR3 data. The challenge was in the data analysis of regions with varying populations. In some regions, it is possible that one PWS serves multiple zip codes. It is also possible that multiple PWS's could be operation in a single zip code. These challenges would have to be addressed on a case-by-case basis as needed.

The population data was provided from the Untied States 2010 census. The census was a great resource because it not only provided data on population, but also provided data on items such as age and number of households in each zip code (U.S. Census Bureau, 2011). Once the census data was linked by zip code to the UCMR3 data, both the chromium data and the entirety of the census data could be accessed for any specific zip code.

GIS Application

To gain a better idea of population densities, a map was first created of the populations of all the zip codes in the lower 48 Untied States. It was chosen to focus only the lower 48 states since both Alaska and Hawaii historically have low concentrations of chromium. This population map can be seen in Figure 1 with capital cities denoted with a green dot.

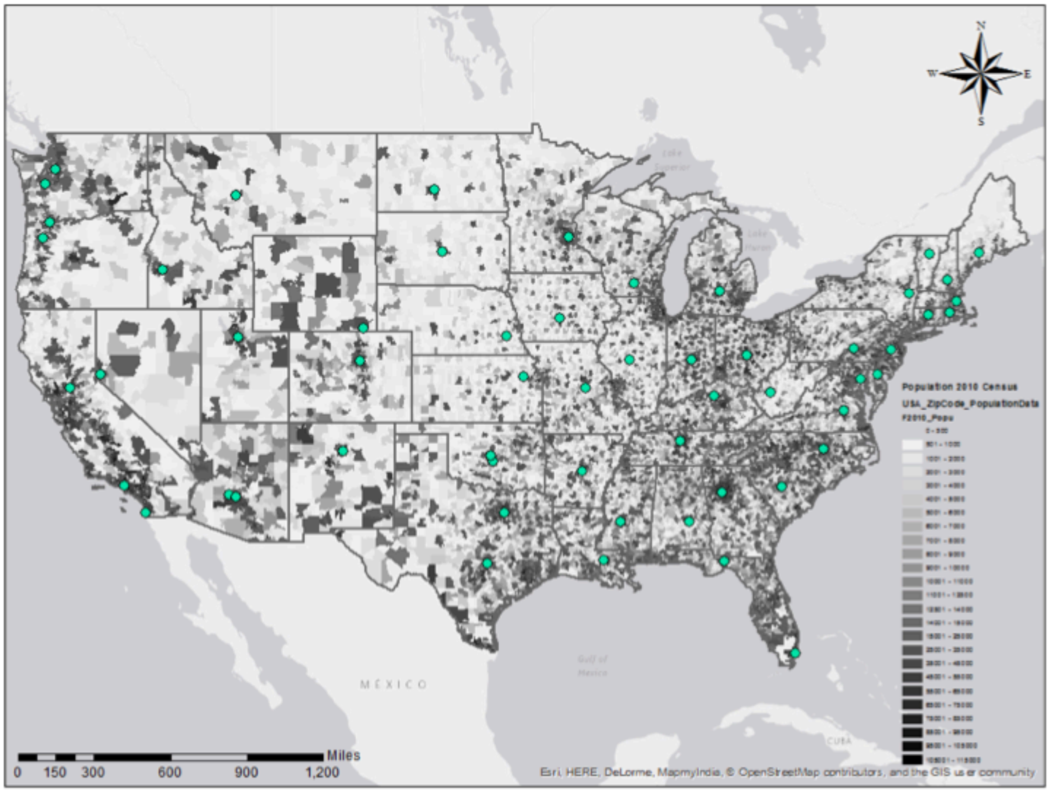

Figure 1. Total Population of Lower 48 United States by Zip Code.

Soon after the map was created it was noticed that many of the zip codes had populations of less than 10,000. Since the UCMR3 data was only for PWS's serving 10,000 or more people, it was unnecessary to show those zip codes that had populations less than 10,000. A modified map was created to reflect only the zip codes with populations over 10,000 and can be seen in Figure 2.

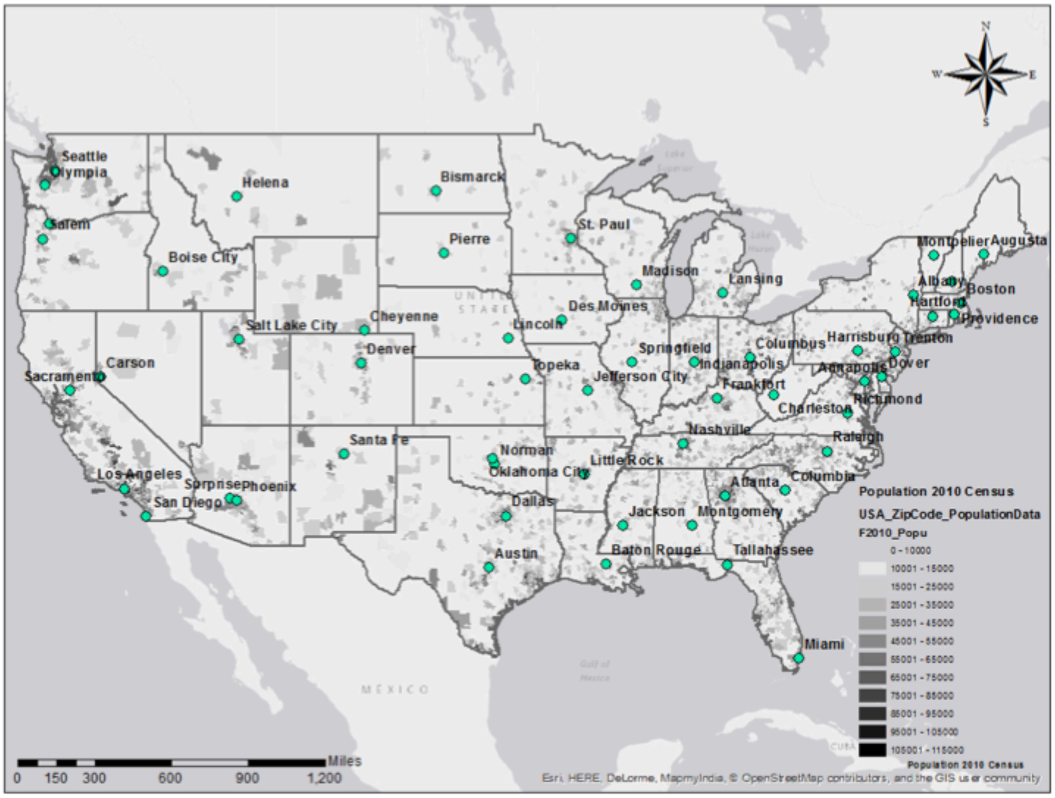

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Figure 2. Modified Population of Lower 48 United States by Zip Code

The modified map in Figure 2 reflects those zip codes with populations above 10,000 and is better suited for comparisons to the UCMR3 data. As expected, it can be seen in Figure 2 that the majority of the larger zip code populations exist on the northeastern and southwestern coastal regions. The largest population found in any zip code is just below 115,000.

The first chromium map that was chosen to map was the maximum values of TotCr found during the routine monitoring of the PWS's involved in the UCMR3 data. It is important to remember that TotCr is a combination of both oxidations states Cr(III) and Cr(VI) and these concentrations are measured at the entry point of the distribution system. Even though the Cr(III) oxidation state is not harmful, it can further oxidize to Cr(VI) under conditions that occur in a water distribution system. The map of maximum TotCr concentrations can be seen in Figure 3.

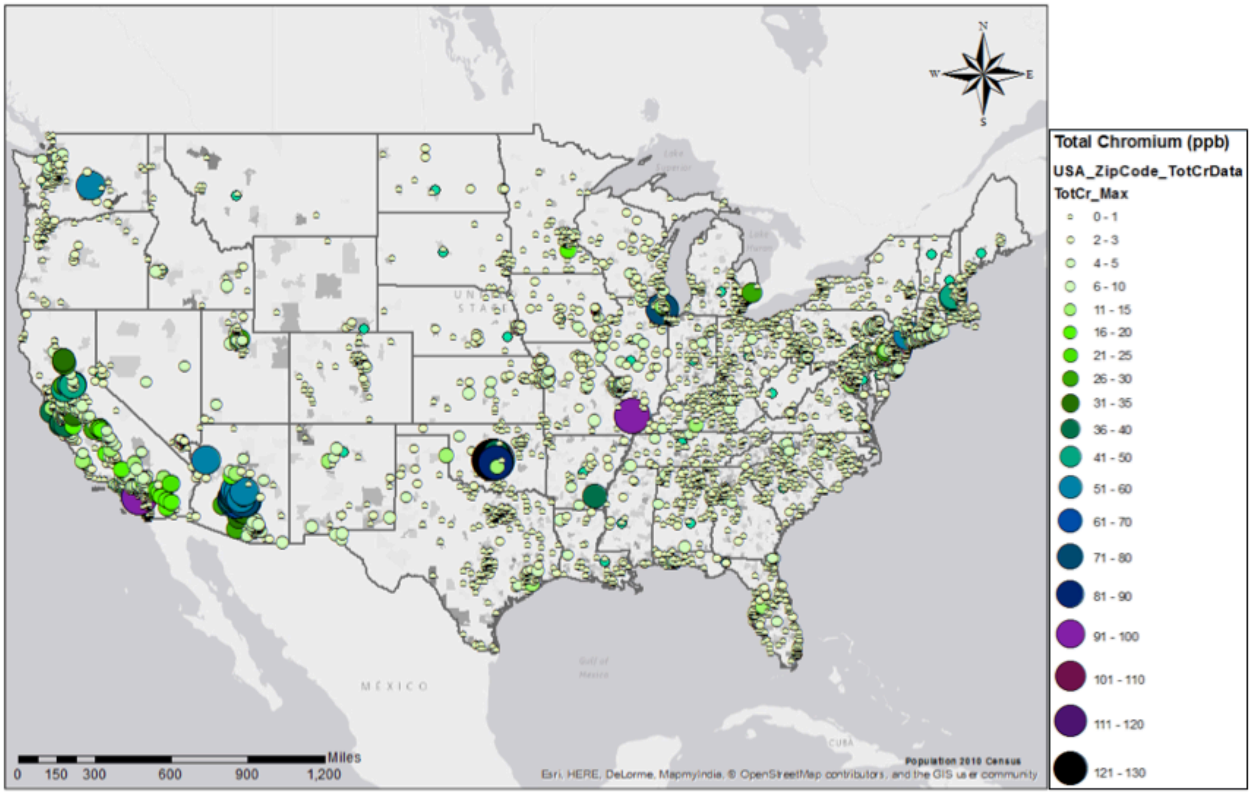

Figure 3. Maximum Concentration of Total Chromium in the Lower 48 United States

While there are many small occurrences of TotCr throughout the lower 48 United States, the larger concentrations are found in the Southwest and Midwest regions. Some of these concentration values are so high that they are out of compliance with the 100 ppb EPA regulation that is currently in place. Since these maximum values could be isolated incidents and not should be considered normal, a more accurate idea of the TotCr concentrations found in needed to be mapped. As such, Figure 4 was created to show the average TotCr concentrations in the lower 48 United States with the capital cities indicated by green dots.

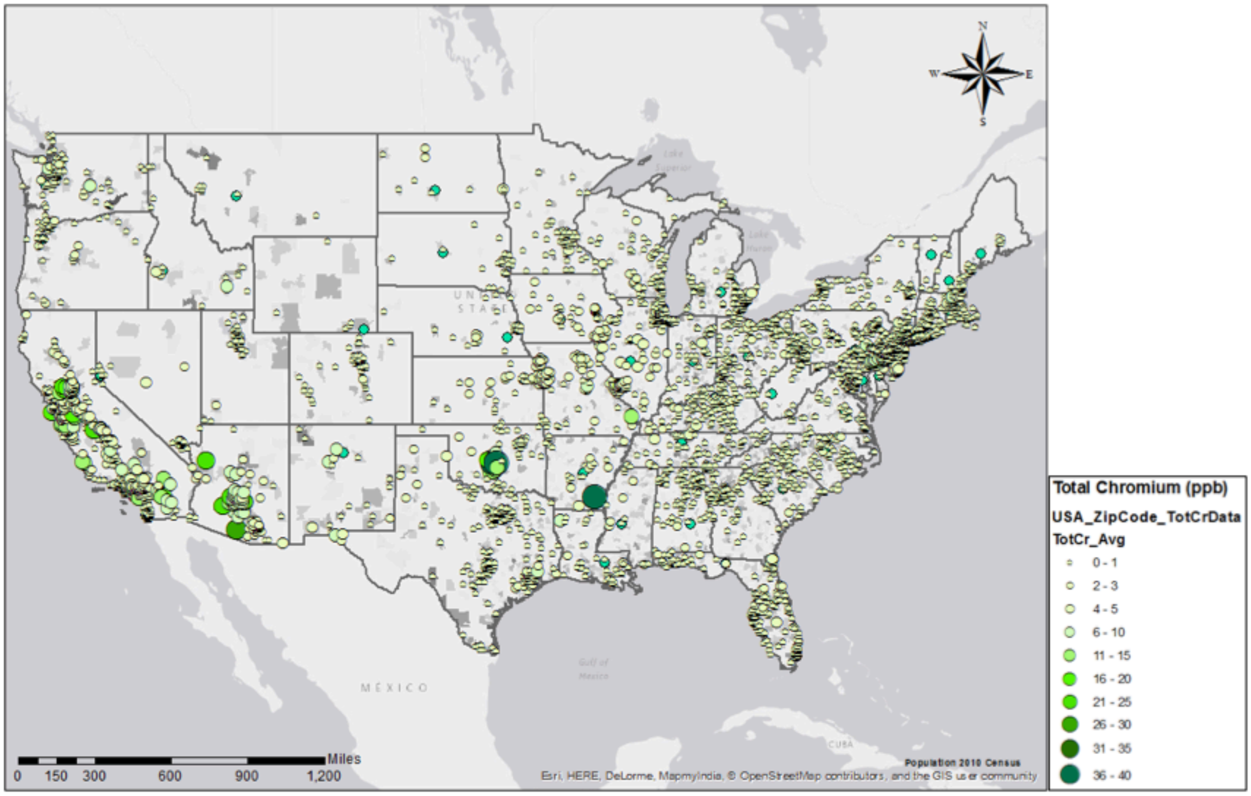

Figure 4. Average Concentration of Total Chromium in the Lower 48 United States

It can immediately be observed with the average values that the overall concentrations of TotCr are much smaller. Since it is highly unlikely that federal regulation of TotCr would ever go below 10 ppb, Figure 4 can be simplified even more to only show the average TotCr concentrations above 10 ppb. This modified map of average TotCr concentrations can be seen in Figure 5.

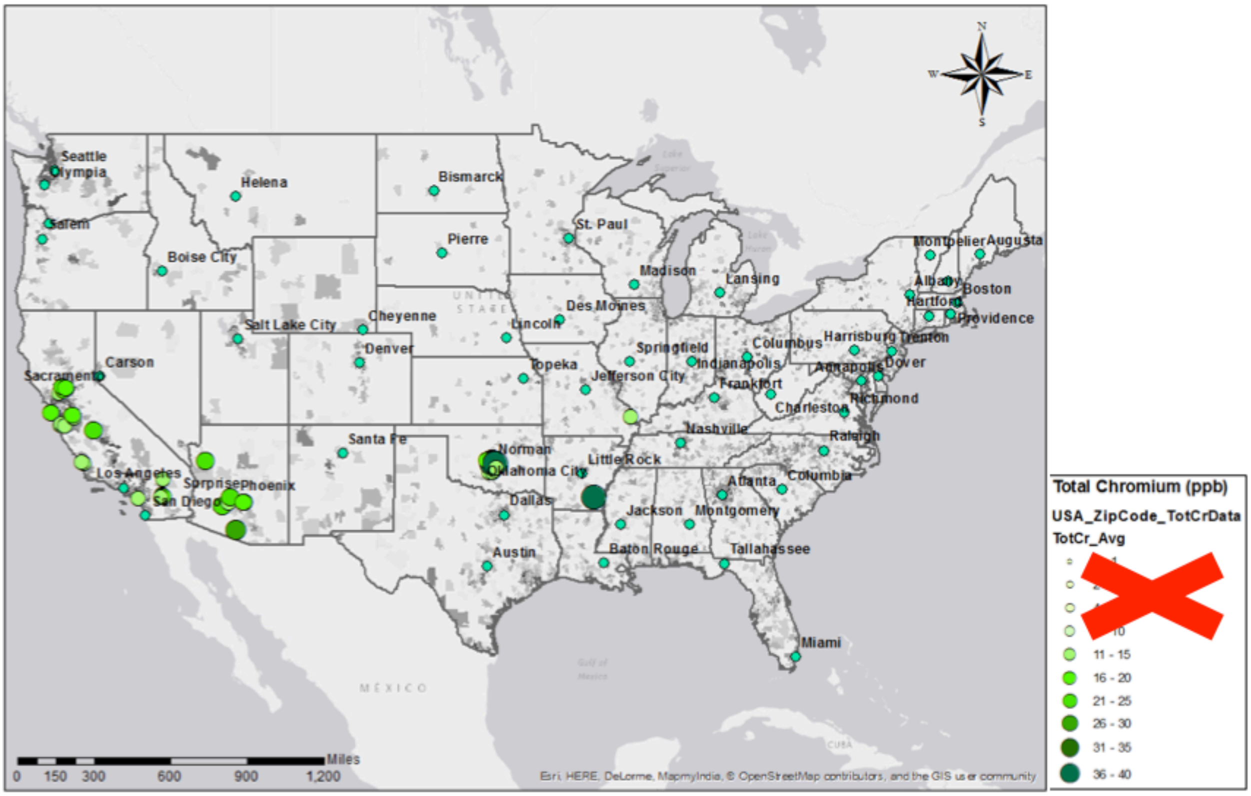

Figure 5. Average Concentrations of Total Chromium above 10 ppb in the Lower 48 United States

It can now be observed that there are only a few areas with consistent averages of TotCr above 10 ppb. These areas are mostly isolated to California, Arizona and the Midwest. Now that the occurrence of TotCr has been seen, comparisons can be made to the harmful oxidation state of chromium in Cr(VI). It is important to note that Cr(VI) concentrations cannot exceed those of TotCr. Just as with TotCr, it was decided to first map the maximum values of Cr(VI) found during the routine monitoring of the PWS's involved in the UCMR3 data. This was done to show areas that are susceptible to contamination, even if the high concentration values were representative of seasonal changes or temporary contamination events. These maximum Cr(VI) values can be seen in Figure 6.

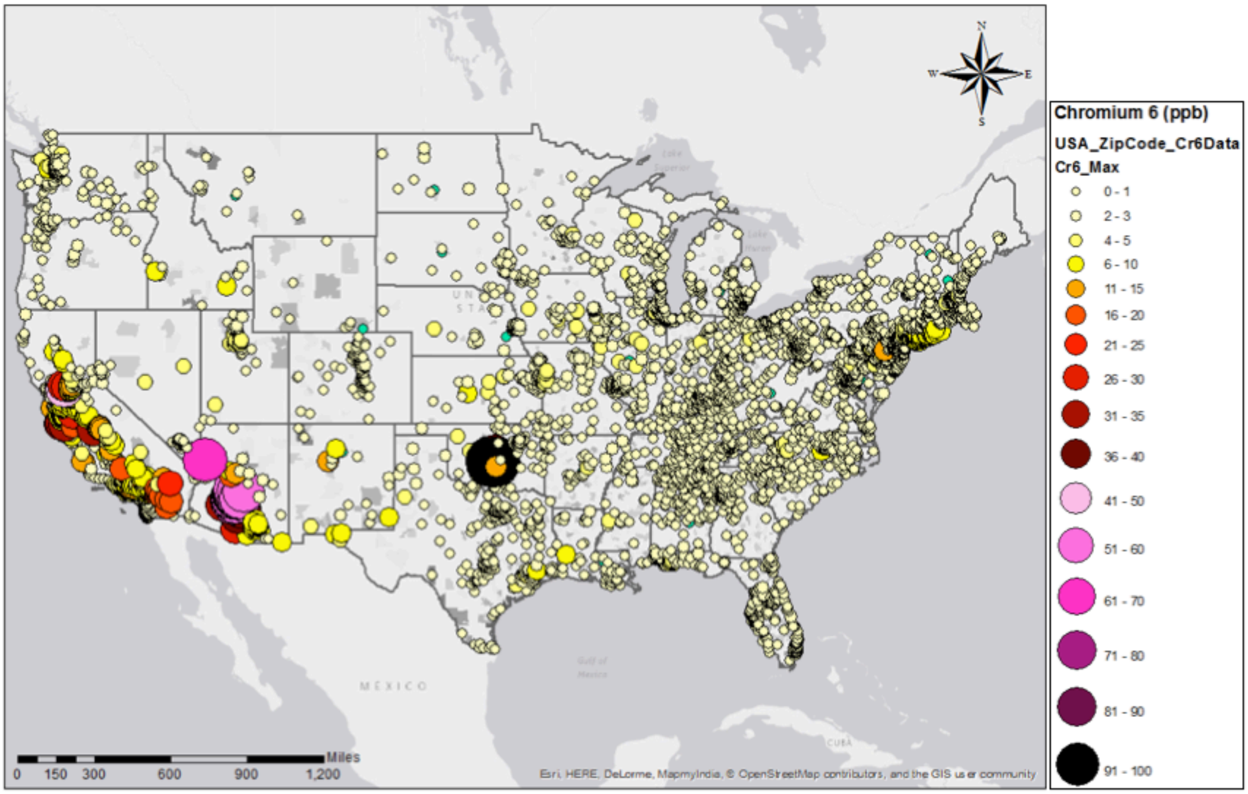

Figure 6. Maximum Concentration of Chromium(VI) in the Lower 48 United States

When considering California's newly implemented MCL of 10 ppb for Cr(VI) there are many areas throughout the lower 48 United States with maximum Cr(VI) concentrations that would be out of compliance with this regulation. While there are many regions above 10 ppb, there are even a few regions with as much as 100 ppb, which is the current MCL for TotCr. However, similar reasoning could be used with the Cr(VI) data that was used with the TotCt data, where these maximum values could be isolated incidents and do not represent constant, normal conditions. To provide a more accurate idea of the Cr(VI) concentrations found and their occurrence, a separate map needs to be created. This separate map can be seen in Figure 7 and shows the average Cr(VI) concentrations in the lower 48 United States with the capital cities indicated by green dots.

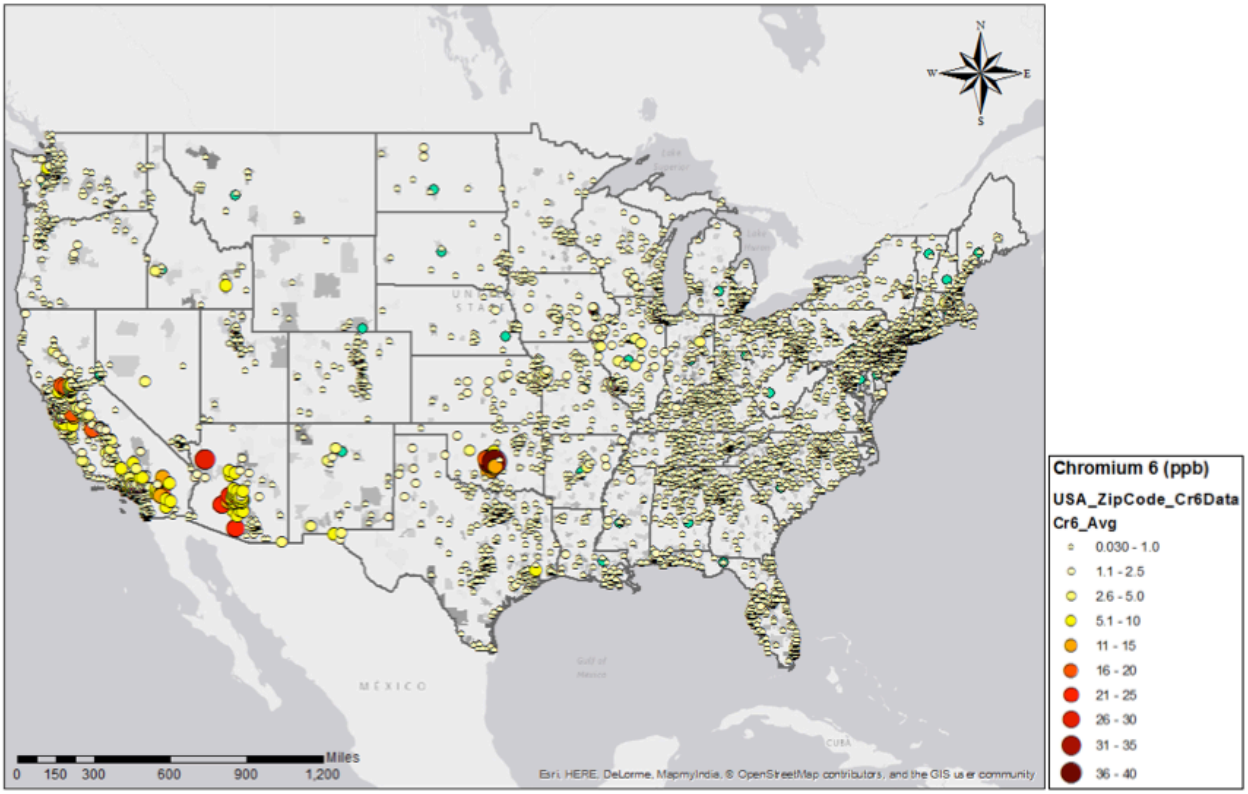

Figure 7. Average Concentration of Chromium(VI) in the Lower 48 United States

Similar to the TotCr data, it can immediately be observed that the average concentration values of Cr(VI) are much smaller. If a federal regulation of Cr(VI) was implemented similar to what was done by the State of California, it is highly unlikely that it would be lower than 10 ppb. As such, the map in Figure 8 was created to simplify the map in Figure 7 to only show the average Cr(VI) concentrations above 10 ppb.

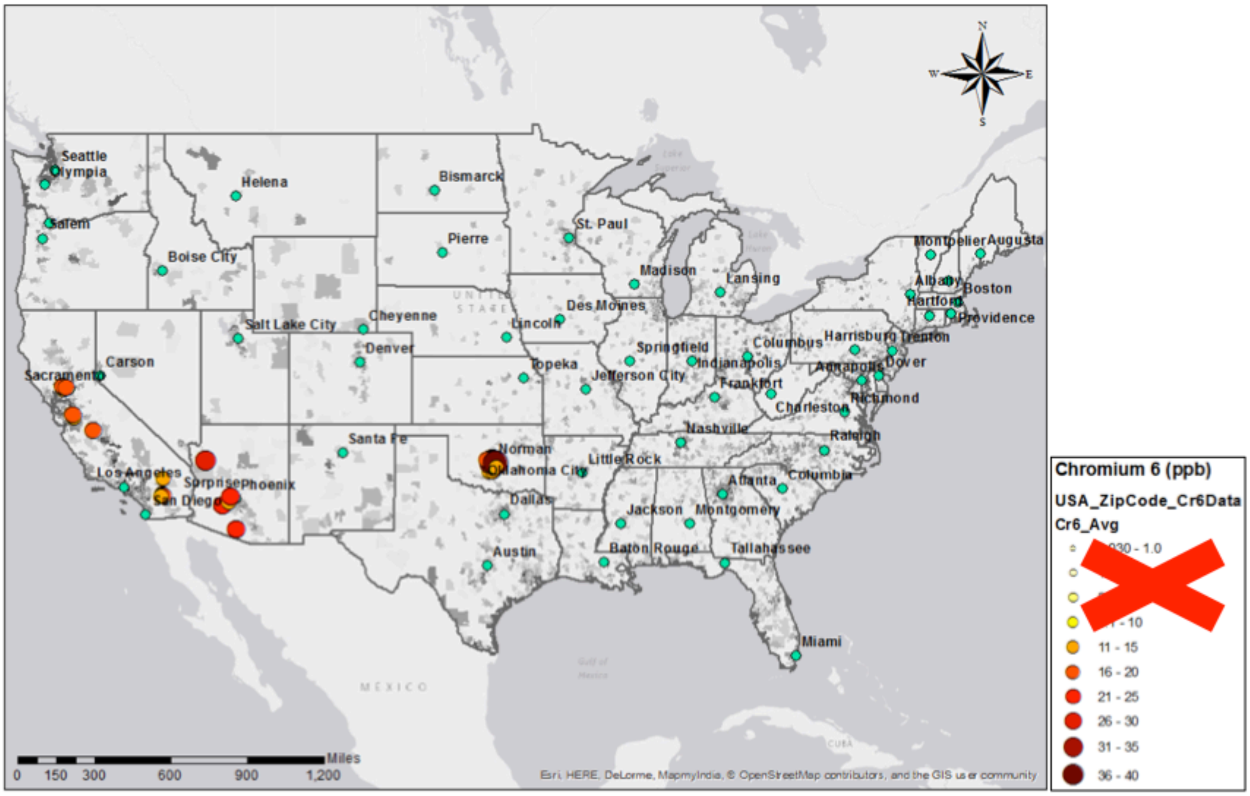

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Figure 8. Average Concentrations of Chromium(VI) above 10 ppb in the Lower 48 United States

Now only the regions with consistent averages of Cr(VI) above 10 ppb are observed in Fiugre 8. Since there are only three main regions where Cr(VI) concentrations are found, these regions are highlighted in Figure 9.

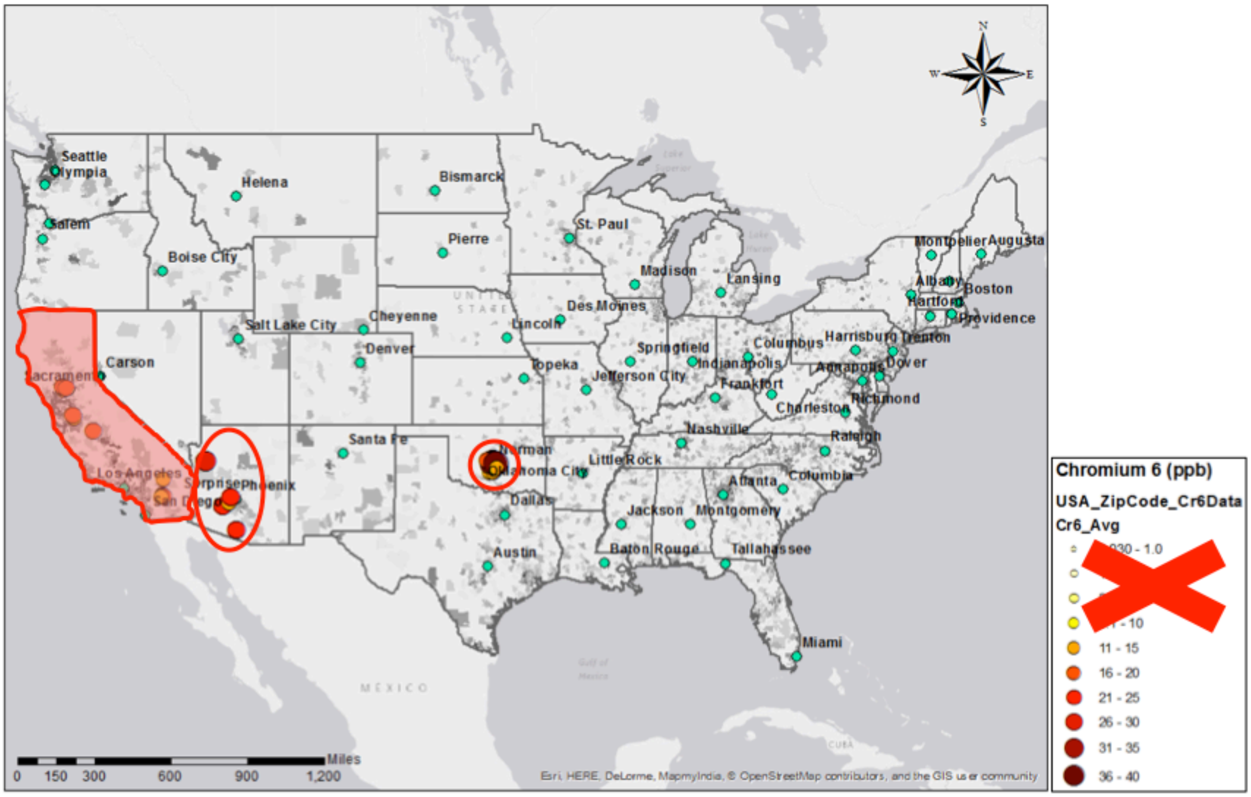


Figure 9. Regions with Average Concentrations of Chromium(VI) above 10 ppb in the Lower 48 United States

These three regions in Figure 9 are classified as the entire State of California, southwestern Arizona, and central Oklahoma. Due to the fact that the State of California is already regulating Cr(VI) with the MCL of 10 ppb, which has been previously discussed, that region is not of concern for further regulation. As a result of California's more stringent Cr(VI) regulation, it is anticipated that the high Cr(VI) concentrations seen in Figure 9 will no longer exist in the future.

It was chosen to look at the central Oklahoma region in more detail, as it has the higher average concentrations of Cr(VI). This detailed map of central Oklahoma can be seen in Figure 10.

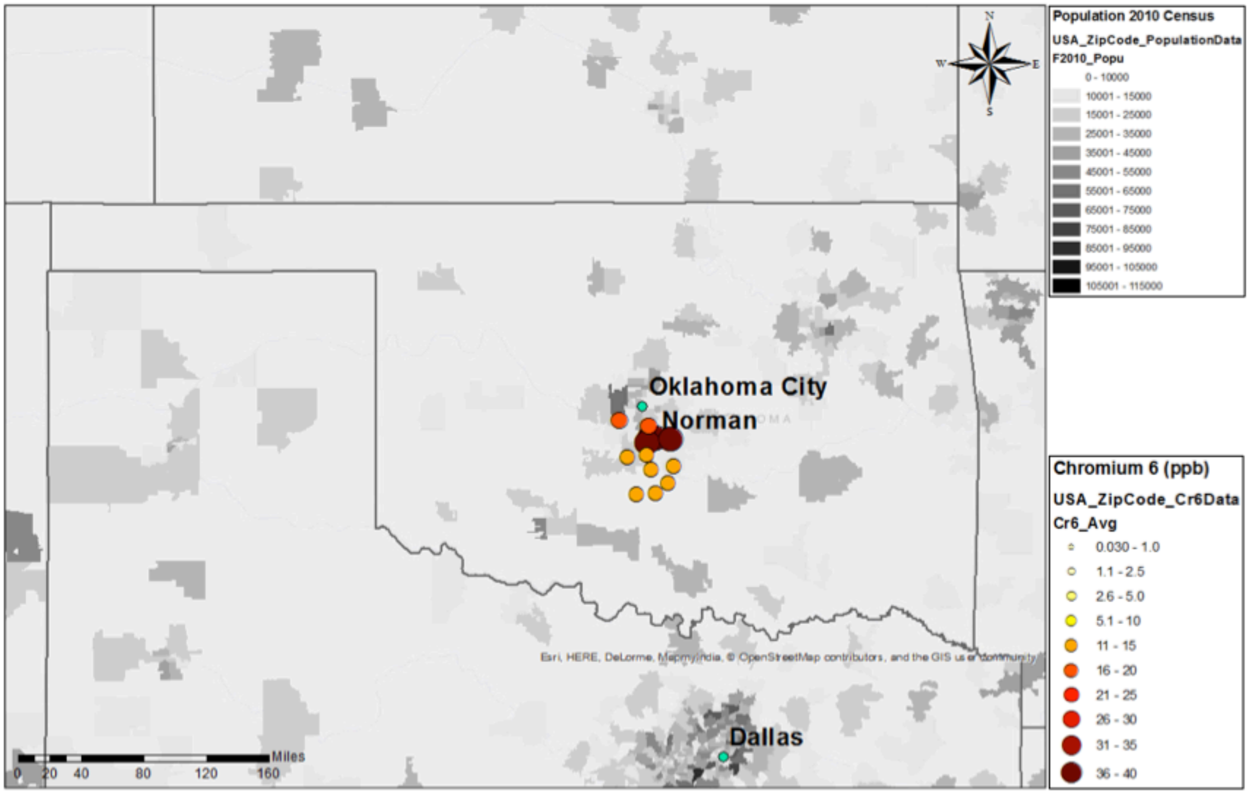
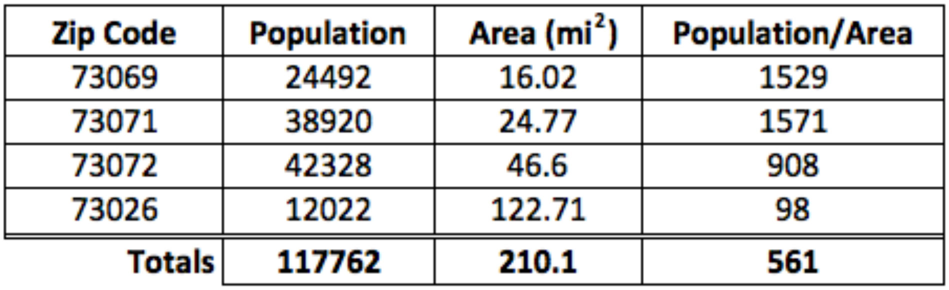


Figure 10. Average Concentrations of Chromium(VI) above 10 ppb in the State of Oklahoma

Looking at Figure 10 and the State of Oklahoma as a whole, it can immediately be observed that there are many zip codes that fit the criteria of having more than 10,000 people, but have no Cr(VI) contamination. These zip codes are also subject to UCMR3 and are required to report Cr(VI) contamination in drinking water, but it can be seen in Figure 10 that the only zip codes that have Cr(VI) contamination are found near and around the city of Norman.

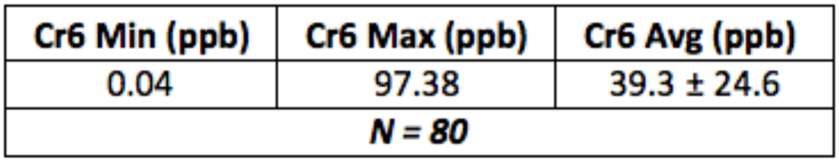
Using the data attribute tables of the combined data in ArcGIS, it was further investigated to find out which zip codes had the highest average values of Cr(VI) in the city of Norman. When these zip codes were analyzed, there were four zip codes with high concentrations of Cr(VI) and it was evident that they all shared the same data. This is was an indication that the populations in these four zip codes were all being served by the same PWS. It could then be assumed that the one or more sources being treated at this PWS was contaminated with Cr(VI). Both the population data and Cr(VI) data for these four zip codes was exported and can be seen in Tables 1 and 2.

Table 1. Population & Density Data for the Zip Codes with High Average Chromium(VI) Concentrations in Norman, Oklahoma



Zip Code	Population	Area (mi^2)	Population/Area
73069	24492	16.02	1529
73071	38920	24.77	1571
73072	42328	46.6	908
73026	12022	122.71	98
Totals	**117762**	**210.1**	**561**

Table 2. Chromium(VI) Data for the Zip Codes with High Average Chromium(VI) Concentration in Norman, Oklahoma



Cr6 Min (ppb)	Cr6 Max (ppb)	Cr6 Avg (ppb)
0.04	97.38	39.3 ± 24.6
N = 80		

The data in Table 1 shows that in 2010, almost 120,000 people were being affected by high average concentrations of Cr(VI) in their drinking water which could be potentially be harmful if ingested (U.S. Census Bureau, 2011). However, it can also be seen in Table 2 that there is a large standard deviation of 24.6 ppb. This deviation could be from an isolated incident where there was a peak in Cr(VI) concentrations, but since the sample size was 80, it is more likely that this area experiences seasonal fluctuations in Cr(VI) concentrations due to water availability. Regardless, the average concentration of Cr(VI) is still almost four times greater than California’s MCL.

Summary

The example of analyzing the area of Norman, Oklahoma and the high concentrations of Cr(VI) that exist in that area are a good example of the limitations brought on by the UCMR3 data using zip codes to represent data collected. When the map was initially viewed, it looked like there were potentially multiple PWS that were experiencing high concentrations of Cr(VI). On closer analysis of the area, all the high values were from a single PWS. This also causes limitations when multiple PWS are providing water to a single zip code. While using ArcGIS to map the chromium occurrences across the lower 48 United States, it is important to remember these limitations brought on by using zip codes as the common link between the different types of data.

The maps did provide a clear look of which regions were affected by chromium contamination as well as the population in these areas. It was initially expected that there would be more areas affected by chromium contamination when the maps showed only three main regions with high average concentrations of Cr(VI). Of these three regions, the largest one (California), has already implemented a regulation to bring those concentrations down.

This provides an interesting argument as to whether or not there should be a federal regulation of Cr(VI). On one side, it could be argued that since only two previously unregulated regions are experiencing high average concentrations of Cr(VI), it would be easy to implement a more strict regulation on Cr(VI) on a federal level. However, there is also the argument that since only two regions are affected by these high average concentrations, it would not be worth it to require everyone to follow more strict regulations. Both sides of this argument have economic implications that would also have to be considered.

When discussing the possibility of new chromium regulations in drinking water, it would be ideal to measure chromium at the consumer tap, since the oxidation state can change in the distribution system. Monitoring chromium at the tap would allow each PWS to better understand the individual characteristics of oxidation kinetics that are occurring in the distribution system between the source and actual consumption. While this idea of tap monitoring is ideal, it is not likely considering the economic costs that would be associated with monitoring chromium in multiple locations as opposed to just one at the entry point to a distribution system.

The ideal scenario for any treated water quality for consumption is that there would be no chromium present to avoid potential harm from the probable carcinogenic Cr(VI) oxidation state. However, the costs associated with completely removing chromium from drinking water could be so large it would be unrealistic to expect consumers to pay for the water being delivered to them. This brings up the issue of finding the delicate balance between removing a potential health hazard from drinking water, and essentially providing "over treated" water to consumers at an increased price. This project provided maps of chromium occurrence data that will aid in making decisions in regards to issues like regulation and economic feasibility.

Next Steps

Going ahead, the next step of this project would be to utilize online data storage sites such as CUAHSI HydroDesktop to possibly locate where the contamination of chromium originates from in a watershed. However, this may not be possible in every scenario since the source of the drinking water would have to be from a surface water with chromium data recorded.

References

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Appendix

R Code

```
all <- read.csv("/Users/Nate/USU/CEE 6440/TermProject/UCMR-3-Occurrence-
Data/UCMR3_All.csv", stringsAsFactors = FALSE, header = TRUE)

zips <- read.csv("/Users/Nate/USU/CEE 6440/TermProject/UCMR-3-Occurrence-
Data/UCMR3_ZipCodes.csv", stringsAsFactors = FALSE)

clean_all <- all %>%

  filter(Contaminant == "chromium" | Contaminant == "chromium-6"

         , AnalyticalResultValue != "NA") %>%

  left_join(zips, by = "PWSID")


chrom <- clean_all %>%

  filter(Contaminant == "chromium") %>%

  group_by(ZIPCODE) %>%

  summarise(

    count = n()

    ,avgresult = mean(AnalyticalResultValue)

    ,variation = sd(AnalyticalResultValue)

    ,maxresult = max(AnalyticalResultValue)

    ,minresult = min(AnalyticalResultValue)

  ) %>%

  arrange(desc(count))


chrom6 <- clean_all %>%

  filter(Contaminant == "chromium-6") %>%

  group_by(ZIPCODE) %>%

  summarise(

    count = n()

    ,avgresult = mean(AnalyticalResultValue)
```

```
    ,variation = sd(AnalyticalResultValue)
    ,maxresult = max(AnalyticalResultValue)
    ,minresult = min(AnalyticalResultValue)
  ) %>%
  arrange(desc(count))

write.csv(chrom, "/Users/Nate/USU/CEE 6440/TermProject/chromium.csv")
write.csv(chrom6, "/Users/Nate/USU/CEE 6440/TermProject/chromium_6.csv")
```