Wastewater Pollution from Petrochemical Refining Industries: Modernizing Treatment Technologies & Downstream Impacts

Client: Environmental Integrity Project

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EXECUTIVE SUMMARY

The Clean Water Act of 1972 was created to regulate pollutant discharge into the surface waters of the United States and aims to produce fishable, swimmable waters across the U.S. and eliminate the pollution of navigable waters by 1985. Over the last few decades, petrochemical refineries have expanded capacity and the volume and variety of their discharged pollutants have increased exponentially. Through the Clean Water Act, the Environmental Protection Agency (EPA) must set effluent limit guidelines (ELGs) for discharge based on the best available treatment technologies (BATs). However, revisions have yet to be made since 1985 and standards do not reflect the advances in the BATs used by oil refineries. Our research aims to provide evidence to the Environmental Integrity Project (EIP) to advocate for updated pollution control standards enforced by the Clean Water Act, identify possible explanatory factors for differences in effluent levels, and evaluate the impacts on downstream populations disproportionately affected by refinery discharges.

The study employs an exploratory analysis to examine potential factors such as the age of the facility, state-specific factors, and company-specific factors. Regression analyses are utilized to investigate correlations between refinery characteristics and pollution levels, which reveal insightful trends such as decreased pollution loads and pollution intensity in newer refineries, potentially due to efficiency improvements.

The impacts of petrochemical refineries on air quality have been more largely studied in comparison to water quality. Our research is specifically necessary to identify and determine socially vulnerable downstream communities who would most benefit from having the effluent limitation guidelines (ELGs) updated and Best Available Technologies (BATs) implemented. In addition, our study uses geospatial analysis to compile sociodemographic attributes of downstream populations from each refinery, which is crucial for understanding environmental justice implications. Through analysis using ArcGIS Pro, Hydrological Unit Code 12 (HUC12) sub-watersheds were used to delineate affected communities. The analysis aimed to determine the most affected downstream populations residing in the polluted watersheds. The data collected from here is integrated with EPA's EJScreen sociodemographic data to provide insights into social vulnerability indices. In addition, our research has quantified the drinking water surface intakes impacted due to the larger amounts, concentrations and variety of chemicals discharged into the

waterways. The concern of exponentially higher water treatment costs and presence of untreated chemicals on young children and infants are highlighted in certain regions of the country.

To advocate for updating the ELGs based on BATs, we have reviewed modernized, cost-effective and state-of-the-art wastewater treatment technologies from the past decade for our target pollutants that are available for adoption by the refineries.

Moving forward, we recommend developing a tool based on the final database of downstream sociodemographic attributes to identify environmental justice concerns downstream of point refinery outfall locations. A dashboard representing the different refinery locations along with the states, downstream population attributes of EJ populations, polluted waterways, and the number of drinking water locations can be created for visual aid. We recommend using the technology review as a living document and building a database of technologies being used to mitigate toxic pollutants to refer to when lobbying against the EPA. Lastly, attempting to locate the water systems and subsequently, the drinking water treatment facilities downstream from the refineries and contact them to understand the potential challenges faced will prove the strongest to advocate for updating the ELGs.

The preliminary findings of this study highlight the disproportionate impacts on vulnerable downstream communities, with over half of the communities affected by lax implementation of effluent limitation guidelines. The study identifies hotspots for refinery discharge in states like Colorado, Alabama, Washington, Texas, and Louisiana, indicating concentrated environmental justice concerns in these regions. The integrated approach combining exploratory and geospatial analyses provides a comprehensive understanding of pollution dynamics and their socio-environmental ramifications. By identifying key drivers and vulnerable communities, this study offers valuable insights for policymakers, regulatory bodies, and environmental advocates to formulate targeted interventions and promote equitable environmental stewardship practices. Through continued research and informed decision-making, strides can be made towards mitigating pollution impacts, safeguarding public health, and advancing environmental justice principles across the United States.

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1. INTRODUCTION

This document presents an analysis exploring potential drivers of discharge from petrochemical refineries in the United States and an evaluation of the communities impacted downstream. Our research aims to collect and analyze information that can be used by our client, the Environmental Integrity Project (EIP), to advocate for the U.S. Environmental Protection Agency (EPA) to revise effluent limitation standards, as required under the Clean Water Act (CWA). The CWA of 1972 was created to regulate pollutant discharge into the nation's surface waters. The Act aimed to produce fishable, swimmable waters across the U.S. and eliminate the pollution of navigable waters by 1985 (Kelderman, 2022). As a result, massive investments were administered to wastewater treatment plants to improve water quality. Over half a century later, half of the assessed rivers and streams across the U.S. are classified as impaired. In other words, these bodies of water are not suitable for recreational activities, cannot be used as drinking water sources, and pose a danger to the environment and its inhabitants.

According to the U.S. Energy Information Administration, 124 out of 184 petroleum refineries in the U.S. are operating (US DOE, 2023). These refineries process raw crude oil into fuel products, nonfuel products, and petrochemicals. Over the last few decades, refineries have expanded capacity and the volume and variety of discharged pollutants have increased. As of 2021, 81 refineries discharge approximately half a billion gallons of wastewater on a daily basis (Markow, 2023). Wastewater produced by refineries includes desalter water, processed water, product wash water, water from decoking, and stormwater. Through the Clean Water Act, the EPA must set effluent limit guidelines (ELGs) for discharge based on the best available treatment technologies (BATs). However, revisions have not been made since 1985 and standards do not reflect the advances in the best available technologies used by oil refineries.

Under federal law, the EPA is responsible for periodically reviewing and updating wastewater treatment technologies at least once every five years when the best available treatment systems have been shown to improve. As of the writing of this report, "two-thirds of EPA's industry-specific water pollution standards had not been updated in more than three decades, despite the law's mandate for reviews every five years to keep pace with advances in treatment technologies" (Kelderman, 2022). Currently, limits of discharge apply to a limited number of pollutants and even these are not based on updated BATs. For companies in the oil sector, like petroleum refineries, it only applies to ten pollutants. These include ammonia, chromium, oil, and grease. They do not address a variety of toxic contaminants found in wastewater discharge such as sulfides, nitrogen compounds, dissolved solids, and heavy metals (Wake, 2004). The EPA's lack of enforcement and revision of standards contributes to the impairment of downstream waterways and poses a real threat to public health and aquatic ecosystems.

The ultimate purpose of our study is to provide the EIP with resources that can be used to support their efforts in advocating for the EPA to modernize and update limit standards and enforcement. Through our analysis we are able to review modern wastewater treatment technologies used by oil refineries, identify possible influencing variables on pollution discharge and identify vulnerable communities affected by loosely regulated refinery pollutants.

2. LITERATURE REVIEW

2.1. Clean Water Act

The Federal Water Pollution Control Act, now known as the Clean Water Act, was the first significant United States law to address water pollution. It is the basic structure of pollutant discharge regulation concerning the waters of the US. This act was created to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters" (US Congress, 2002). Its initial objective was to regulate pollutant discharge into surface waters to produce fishable, swimmable waters and eliminate the pollution of navigable waters across the U.S. The 1972 legislation declared two goals: zero discharge of pollutants by 1985 and "fishable" and "swimmable" waters by mid-1983 (Congressional Research Service, 2013). To achieve these goals, the act explicitly structured programs concerned with the improvement of water quality. This law established standards regarding pretreatment for existing and new sources of pollution with allowable concentrations of few pollutants such as ammonia, chromium, biochemical oxygen demand (BOD), and oil and grease (Radelyuk, 2021). The act has been amended several times resulting in refined treatment standards. It requires standards to be based upon the application of the best available technologies economically achievable. In essence, this law governs the regulation and enforcement of requirements concerning waste discharge into the nation's waters, and financial assistance for the development of treatment plants and improvements.

Enacted in 1972, this principal law required all wastewater produced by municipalities and industrial facilities to be treated before being discharged. In addition, it required an increase in federal assistance for municipal treatment plants, streamlined enforcement, and expanded the role of responsibility for states to implement the law daily (Congressional Research Service, 2013). Today the CWA consists of two major parts, one which authorizes federal finances for municipal sewage treatment plant construction and the second centered on regulatory requirements. Under the CWA, the Environmental Protection Agency is obligated to implement comprehensive programs for water pollution control. The primary focus is technologies that achieve higher levels of pollution abatement. Initially, industries were given until July 1, 1977, to implement "best practicable control technology" (BPT) to improve pollution created by discharges. The purpose of BPTs was to control the discharge of conventional pollutants. These pollutants were identified as suspended solids, biochemical oxygen demand, pH, fecal coliform, and bacteria. These pollutants were considered to be pollutants that dissolved oxygen concentration in water which is vital for fish and other aquatic life. By 1989, the act demanded greater pollutant mitigation from BPTs which led industries to use the "best available technology" (BAT) that is economically achievable.

While the primary focus is technology-based requirements established by the federal government, the secondary initiative focuses on the establishment of water quality standards. This includes developing and publishing wastewater standards for the industry, specifying pollutants associated with those standards, and updating information on such. They serve as a backup due to their indication of where additional pollutant control measures are needed in order to achieve the goal of the CWA (Congressional Research Service, 2013). The EPA is required to develop national water quality criteria recommendations for pollutants in surface waters. In addition, the agency issues regulations containing effluent standards for the best available technology and best practicable technology that apply to municipal and industrial dischargers, including steel manufacturing, organic chemical manufacturing, and petroleum refining. Technology-based effluent limitations are a specific numerical value applied to industrial and municipal sources through discharge permits.

While the act imposes technological demands, it falls short of its goal of achieving zero pollutant discharge and making the U.S. waters fishable and swimmable. The CWA requires each state to establish standards for water quality of all bodies of water within the state, however, the EPA has been empowered with an oversight role. The agency relies heavily on making state agencies responsible for implementing the Clean Water Act. Yet, neither the EPA nor state environmental agencies provide effective oversight of major facilities to stay within their pollution control limits (Kelderman, 2022). Consequently, excess amounts of pollutants have been discharged into our nation's waterways. The EPA is obligated to review discharge limitations every five years and revise them as improved technologies, that are better equipped to control pollution, become more available. However, the EPA has allowed for decades to pass without updating pollution standards for various industries and current regulatory limits do not reflect advancements in water treatment technologies. As treatment technologies improve, pollution standards denoted as effluent limits and effluent limitation guidelines are supposed to become more stringent. Technology has advanced, but the guidelines continue to reflect grossly outdated technology standards and, as a result, industrial and municipal sources discharge pollution into the nation's waterways.

2.2. Industrial Source: Petroleum Refineries

Petroleum refineries comprise one of the largest industries in the nation and play a crucial role in the country's economy. Petroleum refining is the process of converting crude oil into more than 2500 products (EPA, 2024). These products include diesel fuel, lubricating oils, feedstock, liquid petroleum gas, aviation fuel, asphalt, and gasoline. By 1970, the petroleum refining industry had become well-established in the US. With 324 refineries in the early 1980s, the country was able to produce about 18.6 barrels per day (HSR, 2003). However, due to a shift in alternate fuel and an increased focus on conservation, the number of refineries has reduced to the current 184. As the world became more aware of the potential hazardous environmental impacts associated with industrial pollution, petroleum refining was an industry addressed in the CWA. Yet, oil refineries release billions of pounds of pollution annually into waterways. According to the Environmental Integrity Project, 81 refineries in the US discharge approximately 1.6 billion pounds of chlorides, sulfates, and other dissolved solids (EIP, 2023). Oil refineries are complex industrial sources that results in variety of emissions into the water. Other substances include process water, heavy metals, nitrogen, and selenium which can kill aquatic life, feed harmful algae, and make waterways harmful to use.

2.3. Water Pollution from Refineries

2.3.1. Summary

Oil refineries release billions of pounds of pollution annually into waterways (Hersher, 2023). This pollution includes but is not limited to, nitrogen, suspended and dissolved solids, heavy metals, and other compounds that can affect aquatic animals and organisms that make waterways unsafe to drink, swim, and fish. Crude oil in refineries is converted into a variety of products including gasoline, motor oil, and jet fuels. Oil refining involves crude distillation, vacuum distillation, catalytic cracking, reforming, and alkylation. Generally, petroleum refineries produce about 0.4-1.6 times of wastewater per unit of crude oil (Thorat, 2022). According to reports in 2019, the world's oil consumption was about 99.93 million barrels per day, indicating the production of around 6500-2400 million liters of wastewater per day (Jain et al., 2020). The number of pollutants discharged poses a significant threat to humans and the environment due to their toxic and carcinogenic properties. Refineries pose a significant environmental challenge due to the release of various harmful pollutants, including nitrogenous compounds, selenium, and nickel. Nitrogenous compounds, such as ammonia and nitrate, can lead to eutrophication in water bodies, disrupting aquatic ecosystems and depleting oxygen levels. Selenium, a trace element found in crude oil, can accumulate in aquatic environments, posing risks to wildlife and human health. Nickel, primarily emitted through refinery processes, is a known carcinogen and can cause respiratory issues and skin allergies. Addressing pollution from refineries necessitates the implementation of robust mitigation strategies, ranging from advanced biological treatment methods to membrane technologies and precipitation techniques, to safeguard both environmental integrity and public health. The following sections delve deeper into the target pollutants' impacts on environmental and human health.

2.3.2. Nitrogenous Compounds

Petroleum refineries produce over 2500 byproduct compounds and chemicals from the different processes that result from extensive water usage in refineries for cooling, distillation, and crude desalting to name a few. The composition of refinery wastewater varies depending on the process involved. Ammonia, nitrates, and nitrites are the dominant nitrogen-containing compounds in refinery wastewater, majorly present in the output streams of crude desalting, crude oil distillation, thermal cracking, hydrotreating, catalytic cracking, and polymerization (Al-Khalid & El-Naas, 2018). Wang et al., analyzed the contribution of petroleum refinery effluents to the chemical mixture of toxic pressure in the environment for different compounds (Wang et al., 2023). They found that 85% of the mixture's toxic pressure was attributed to hydrocarbons and among inorganic compounds, ammonia was the largest toxic contributor.

The report synthesized by the Environmental Integrity Project evaluates the effluents discharged by 81 petrochemical refineries across the United States directly into waterways (Environmental Integrity Project, 2023). The nitrogen discharged was mostly composed of nitrates and nitrites, accounting for approximately 67% of the total. Ammonia and organic forms of nitrogen contributed the remaining. Refinery ammonia effluent restrictions were set by the EPA in 1974, but limits on nitrates or total nitrogen from these plants have never been specified. Furthermore, nitrates are byproducts of the ammonia treatment processes integrated in wastewater treatment systems.

2.3.3. Toxic Metals: Selenium

Selenium is considered a micronutrient. Within the 60-135 range, it is essential for physiological functions (Hansen et al., 2019). However, in excess amounts, it becomes toxic for animals and humans. Nationally, the discharge of selenium into our environment has become a matter of increasing concern (Okonji, 2021). There are two main sources of selenium: naturally occurring and anthropogenic sources. The latter is mainly associated with industrial activities such as energy generation, mining, oil and gas refineries have a faster distribution rate. As a result of such activities, there is an excess of selenium present in the environment. High levels of selenium in aquatic ecosystems can disrupt the balance of organisms, leading to bioaccumulation in aquatic life forms. This bioaccumulation not only affects the health of aquatic species but can also harm birds and mammals that feed on contaminated fish or insects. Furthermore, selenium contamination can impair the reproductive success of certain species, leading to population declines and ecosystem destabilization.

Selenium plays a crucial role in human health. It is essential, as it supports immune system functions, maintains thyroid function, and acts as an antioxidant. However, excessive intake can lead to adverse effects such as selenosis, which is characterized by hair loss, gastrointestinal disturbances, and neurological abnormalities. Chronic selenium toxicity has been reported in areas with naturally high soil and water selenium levels. Whereas, low soil levels raise the possibility of selenium deficiency. In turn, this can lead to weakened immune systems and increased risk of certain diseases. As a result, it is important to balance selenium intake to promote ecological stability and ensure optimal health, highlighting the complex relationship between the environment and human health.

2.3.4. Toxic Metals: Nickel

Nickel, a hard, silvery-white metal, is commonly utilized in combination with other metals to form alloys. It is naturally present in the Earth's crust, and nickel constitutes 6% of the Earth's core. (Tepe, 2014) In many biological systems, nickel typically exists in the form of Ni_2^+ (Begum, W. et al., 2022). The extensive industrial use of nickel compounds has led to a significant increase in both the release and accumulation of nickel in our environment (Mitra et al., 2022, Sharma et al, 2023). The concentration levels of nickel (Ni2+) in refinery wastewater may depend on the geological formation, location, and source rock of a crude petroleum field. (Mansour et al., 2024)

2.4. Effluent Limitation Guidelines Overview

To implement sections 304, 306, and 307 of the Clean Water Act, the EPA developed standards. for the oil refining industry (EPA, 1974). In 1974, standards for best available technologies were developed for the petroleum refining point source category. These standards, most commonly known as effluent limitation guidelines, are national wastewater discharge standards developed by the EPA for various industrial operations (EPA, 1974). ELGs set regulatory standards for wastewater discharged into surface waters and to publicly owned wastewater treatment plants in the US to reduce the discharge of toxic pollutants. These limitations are incorporated into NPDES permits for direct discharges and other mechanisms are used for other discharges. The EPA effluent guidelines are not based on risk studies but rather technology-based which means they are based on the performance of treatment and control technologies for regulated pollutants (Kuzniewski, 2023). The EPA established these technology-based numeric limitations and placed them on certain pollutants from point and non-point sources. There are three types of regulated pollutants, conventional, non-conventional, and toxic. Both conventional and non-conventional pollutants include toxic pollutants. The EPA has identified 126 priority pollutants, of which 65 are considered toxic pollutants that can be found at 40 CFR Part 401.15. Pollutants such as benzene, chromium, lead, nickel, and selenium are included in the list of toxic pollutants subjected to regulation under section 307(a)(1) of the act (*40 CFR 401.15*). This section makes it known that the list of toxic pollutants shall be published and revised based on the toxicity of a pollutant, its persistence, degradability, its effect on organisms in any water, and the extent of such effect (US Congress, 2002). The toxic and priority pollutants lists are essential for the EPA when developing national discharge standards as they can be used as a starting point for numeric limits.

Different control technologies regulate all three types of regulated pollutants. In the EPA's effluent guidelines, there are six control technologies for regulated pollutants. These technologies include best available technology (BAT), best practicable control technology (BPT), best conventional pollutant control technology (BCT), new source performance standards (NSPS), pretreatment standards for existing point sources (PSES), and pretreatment standards for new sources (PSNS) (Kuzniewshi, 2023). BAT, BPT, BCT, and NSPS apply to point source dischargers while NSPS and PSES apply to non-point source dischargers. The EPA makes known the limitations and standards for toxic pollutants through 40 CFR part 419. The guidelines for petroleum refining point source category regarding effluent limitations sets the amount of pollutants that can be reduced within discharge as a result of the application of the best practicable control technology currently available as well as through the application of the best available technology economically achievable (40 CFR Part 419). The EPA evaluates factors such as age, size of facility, manufacturing processes, cost, control, and wastewater treatment technology available to establish effluent levels as denoted in section 304(b)(2) of the CWA. The aim of including these factors is to reduce the concentration of regulated pollutants discharged into receiving waters to reduce their effect on human and environmental health. In the US, the effluent limitations cover wastewater discharged at over 140 petroleum refineries.

Any existing discharges subject to 40 CFR 419 authorized by the CWA must achieve the effluent limitations for ammonia as N representing the reduction of discharge through the use of BAT:

Table 1: *BAT Effluent Limitations for Ammonia as N provided by 40 CFR part 419*

	BAT Effluent Limitations		
Subcategory	**Pollutant or pollutant property**	**Maximum for any 1 day**	**Average of daily values for 30 consecutive days shall not exceed**
		Metric units (kilograms per 1,000m^3 of feedstock)	
Topping	Ammonia as N	2.81	1.27
Cracking	Ammonia as N	18.8	8.5
Petrochemical	Ammonia as N	23.4	10.6
Lube	Ammonia as N	23.4	10.6
Integrated	Ammonia as N	23.4	10.6

While standards for BATs were established in 1974, by October 1982, the EPA promulgated the final effluent limitation guidelines for the petroleum refining point source category. Final effluent limits for the best available technology economically achievable addressed pollutants such as phenol, pH, and chromium. Essentially, BATs are used as the most efficient and cheapest way to meet the requirements authorized in the CWA for petroleum refineries (Radelyuk et al., 2021). This type of technology uses "in-plant" and "end-of-pipeline" technologies. In-plant technologies control the number of pollutants in processing water. This is done through preliminary treatment methods such as sour water stripping, water reuse, and separation of stormwater and process water. This approach attempts to reduce the burden of end-of-pipeline technologies which systems aim to eliminate or significantly reduce the number of toxic pollutants in final discharge (Radelyuk et al., 2021). Currently, under BAT, production-based limits for pollutants comprise ELGs. Presently, effluent limits regulate "BOD5, TSS, COD, oil and grease, phenolic compounds, ammonia, sulfide, and chromium" (EPA, 2019).

The EPA conducts a study of wastewater discharges from petroleum refineries to assess the efficiency of the technologies used. A more recent study conducted by the EPA assessed the end-of-pipeline technologies. A part of the assessment compared the current technologies being used by refineries to the technologies that have been identified as the best available technology that are concerned with existing ELGs. The study identified the BAT used in end-of-pipeline treatment includes "...equalization and storm water diversion, primary oil and solids removal, secondary oil and solids removal, biological treatment to reduce BOD and COD, filtration or other final polishing steps following biological treatment" (EPA, 2019). The EPA compiled the data on wastewater treatment for 129 of the 143 petroleum refineries. The table below summarizes the number of operating refineries using BAT technology.

2.5. Best Available Technologies

2.5.1. Modern Technologies

Existing and advanced measures for elimination, reduction and control of pollutants are described in this section. Recent advancements have accelerated the shift towards more efficient and environmentally conscious solutions. The best available technologies discharge levels for refinery pollution emitted to water are as shown in Appendix A. Used, either singly or in combination, the reduction measurements represent BAT solutions achievable when implemented in the appropriate circumstances. The table (refer Appendix A) assessing the best modern available technology for refinery pollutants like selenium, nitrogen, and nickel encapsulates an overview of cutting-edge solutions aimed at mitigating these contaminants' environmental impact. It is important to note that there are standards and technologies for some pollutants currently. However, our analysis highlights only technologies used for selenium, nickel, and nitrogen. For selenium removal, technologies such as ion exchange resins and biological treatment systems emerge as frontrunners, offering efficient and cost-effective methods for reducing selenium concentrations in wastewater streams. Ion exchange resins demonstrate high selectivity for selenium ions, facilitating their removal from aqueous solutions, while biological treatment harnesses microbial processes to metabolize selenium compounds into less harmful forms.

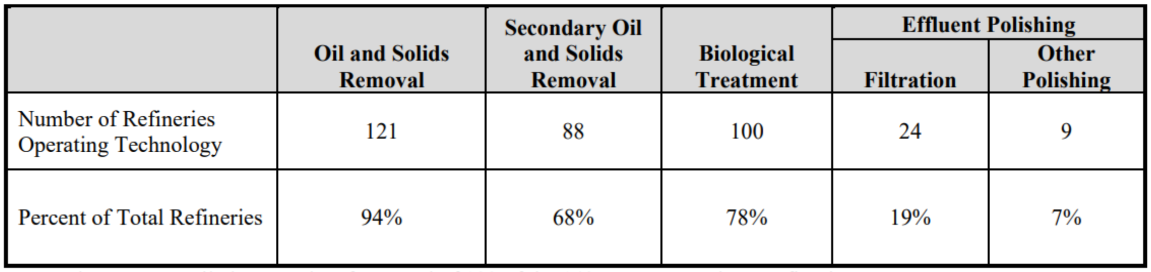
In addressing nitrogen pollution, the table (refer Appendix A) highlights the efficacy of advanced biological treatment methods such as nitrification-denitrification processes and enhanced nutrient removal systems. These approaches leverage specialized microbial consortia to convert ammonia and other nitrogenous compounds into nitrogen gas, thereby eliminating nitrogen-based pollutants from refinery effluents. Additionally, the integration of membrane technologies like membrane bioreactors (MBRs) enhances nitrogen removal efficiency by providing a physical barrier for separating nitrogen-rich biomass from treated water, resulting in higher purity effluents.

For nickel remediation, the table underscores the significance of precipitation and adsorption processes in effectively removing nickel ions from refinery wastewater. Precipitation techniques utilize chemical agents to induce the formation of insoluble nickel compounds, which can then be separated through sedimentation or filtration processes. Meanwhile, adsorption technologies employ specially tailored adsorbents such as activated carbon or ion exchange resins to selectively capture nickel ions from aqueous solutions. By presenting these diverse technological solutions, the table serves as a valuable resource for refinery operators seeking to adopt the most suitable strategies for mitigating selenium, nitrogen, and nickel pollutants in their wastewater streams.

2.5.2. Technologies in the United States

Implementation of BAT is a driving factor of effluent limitation guidelines. Best available technologies, as described in section 5 of the EPA acts 1992 to 2007, are the most effective technologies reasonably accessible used in order to achieve a high level of protection of the environment as a whole (EPA, 1985). The principle of the BAT is to find the most efficient and cheapest way to meet the requirements authorized in the CWA (Radelyuk et al., 2021). This type of technology uses "in-plant" and "end-of-pipeline" technologies. In-plant technologies control the number of pollutants in processing water. This is done through preliminary treatment methods such as sour water stripping, water reuse, and separation of stormwater and process water. This approach attempts to reduce the burden of end-of-pipeline technologies which systems aim to eliminate or significantly reduce the number of toxic pollutants in final discharge (Radelyuk et al., 2021).

In 2019, the EPA conducted a detailed study on wastewater discharged from petroleum refineries to assess the efficiency of the technologies used. A more recent study conducted by the EPA assessed end-of-pipeline technologies. A part of the assessment compared the current technologies being used by refineries to the technologies that have been identified as the best available technologies that are concerned with existing ELGs. The study identified the BAT used in end-of-pipeline treatment includes "...equalization and storm water diversion, primary oil and solids removal, secondary oil and solids removal, biological treatment to reduce BOD and COD, filtration or other final polishing steps following biological treatment" (EPA, 2019). The EPA compiled the data on wastewater treatment for 129 of the 143 petroleum refineries. The table below summarizes the amount of operating refineries using BAT technology.



	Oil and Solids Removal	Secondary Oil and Solids Removal	Biological Treatment	Effluent Polishing	
				Filtration	Other Polishing
Number of Refineries Operating Technology	121	88	100	24	9
Percent of Total Refineries	94%	68%	78%	19%	7%

***Table 2**: Wastewater Treatment Technologies at 129 Petroleum Refineries Provided by EPA 2019 Report*

2.5.3. Technology and Standards in Europe

The European Union (EU) regulates water pollution under a number of directives. The Water Framework Directive of 2000 mandates achieving good water quality in EU waters. The Industrial Emissions Directive 2010/75/EU Integrated Pollution Prevention and Control regulates pollution into air and water from industrial sources. A 2016 report on BATs for wastewater from the chemical industry presented updated data on effluent standards, including the average discharge of nitrogen (N) and nickel (Ni) into both air and water (Brinkmann et al., 2016). Additionally, it outlined the current methods employed in Europe for minimizing air and water emissions and discussed the Best Available Techniques (BAT) for enhancing pollution control. The limits in the EU report are defined by the limit of detection (LOD) and quantification (LOQ). The LOD is defined by the minimum concentration that can be detected. The LOQ is the inference of other processes in detection such as nitrification and denitrification in the detection of soluble nitrogen.

1) Effluent Information (Brinkmann et al., 2016)

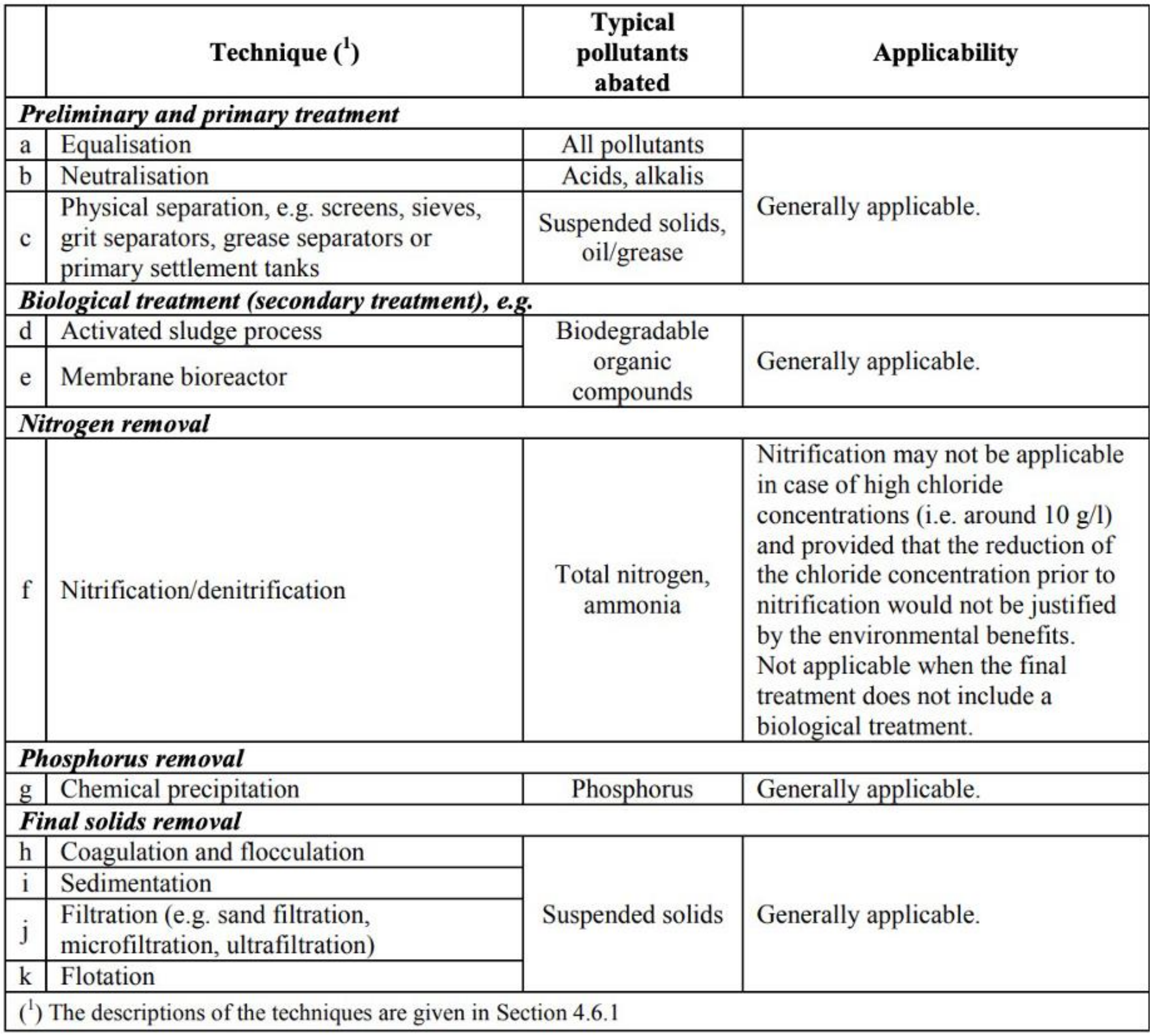
For selenium, the EU report did not provide clear effluent information. The only available data in the EU report is the range of selenium concentration in the refinery wastewater (0.00 to 0.05 mg/L, from 5th percentile to 95 percentile), the average concentration is 0.02 mg/L.

For nickel, average Ni levels in the effluents of wastewater treatment plants (WWTPs) are generally ≤ 50 µg/L. Though higher effluent concentrations exceeding 50 µg/l have been reported in specific WWTPs. The EU report mentioned biological treatment methods for nickel abatement, with efficiency ranging approximately from 50 to 80%. This indicates that biological treatments can reduce nickel concentrations.

For nitrogen, the situation is more complex. Total nitrogen includes nitrites, nitrates, ammonia, ammonium, and organic nitrogen compounds. For total nitrogen, average effluent concentrations are below 40 mg/L. Abatement efficiencies range between 30%-95%, but more generally from 43.8 % to 91.9 % (10th to 90th percentile) with a median of 78.4 %. For inorganic nitrogen, abatement efficiencies ranged from 25.7 % to 93.7 %, but more generally from 46.4 % to 91.3 % (10th to 90th percentile) with a median of 84.4 %, and average effluent concentrations below 35 mg/L. For Ammonia (NH_4-N), abatement efficiencies for loads reported for 23 WWTPs range from -9.3 % to 99.6 %, but more generally from 13.8 % to 98.1 % (10th to 90th percentile) with a median of 90.5 %.

2) BAT Recommendations

From the EU Report 2016, The Best available technologies (BAT) to abate out target pollutants – selenium, nickel, and nitrogen related compounds, include equalization, neutralization, etc. (EU Report 2016). The BAT mentioned in the EU report mainly focused on abate nitrogen related compounds. The guideline for Ni is emission exceed 5 kg/year, for TN is 2.5 t/year, and for N_{inorg} is 2 t/year. However, there are no guidelines for Se.



	Technique (1)	Typical pollutants abated	Applicability
Preliminary and primary treatment			
a	Equalisation	All pollutants	Generally applicable.
b	Neutralisation	Acids, alkalis	
c	Physical separation, e.g. screens, sieves, grit separators, grease separators or primary settlement tanks	Suspended solids, oil/grease	
Biological treatment (secondary treatment), e.g.			
d	Activated sludge process	Biodegradable organic compounds	Generally applicable.
e	Membrane bioreactor		
Nitrogen removal			
f	Nitrification/denitrification	Total nitrogen, ammonia	Nitrification may not be applicable in case of high chloride concentrations (i.e. around 10 g/l) and provided that the reduction of the chloride concentration prior to nitrification would not be justified by the environmental benefits. Not applicable when the final treatment does not include a biological treatment.
Phosphorus removal			
g	Chemical precipitation	Phosphorus	Generally applicable.
Final solids removal			
h	Coagulation and flocculation	Suspended solids	Generally applicable.
i	Sedimentation		
j	Filtration (e.g. sand filtration, microfiltration, ultrafiltration)		
k	Flotation		
(1) The descriptions of the techniques are given in Section 4.6.1			

Table 3. *The Summary of the BAT in the EU Report 2016 (Brinkmann et al., 2016)*

There is no technique for removing selenium in Table 3, however, the techniques related to Final solids removal like Sedimentation might be helpful in reducing Se. The filtration and activated sludge process (Gutiérrez-Sánchez et al, 2023) could be used to reduce Ni. The nitrogenous compounds could be reduced by nitrification/denitrification in primary and secondary treatment. Equalization could reduce all types of pollutants.

2.6. Ecological & Human Health Impacts

2.6.1. Nitrogenous Compounds

Nitrogen-containing compounds impact the environment in its various forms and compounds when emitted through both air and water. While nitrogen is naturally present in the environment, excess nitrogen in the air and water contributes to nutrient pollution, one of the most pervasive, expensive, and difficult environmental issues faced by the United States (EPA, n.d.). Currently, human activity adds at least as much fixed nitrogen (N) to ecosystems as all other natural sources combined. Many refineries don't have a denitrification process to remove nitrates - no EPA regulations for nitrates, only ammonia. Through land transformations, humans contribute more than 50 million metric tons of nitrogen (Smith et al., 1999). Smith et al., evaluate the impacts of nitrogen on human health and ecosystems, and deduce the strong motive to reduce nitrogen emissions from traffic, industrial sources, agricultural, and other sources, as the economic benefits of better environmental quality surpass the costs of reduction efforts.

Body size and ability to adapt to the environment decrease with increasing toxicity (Camargo et al., 2005). This poses a serious threat to smaller organisms like freshwater invertebrates whose tolerance is 10 mg/l nitrate, which is five times lower than the standard for drinking water.

2.6.1.1. Environmental Impacts

- **Eutrophication**

Research on eutrophication in dynamic waterbodies, including river and stream eutrophication has not kept up with that on stationary water bodies like lakes (Dodds & Smith, 2016). Eutrophication causes exponential increases in algae growth that deplete oxygen levels of the water, which is necessary for aquatic life to thrive. This in turn disrupts habitats, food sources, and water quality, and in extreme cases leads to the mass death of fish and other organisms (Dorgham, 2014). Consumption of water infected by eutrophication is also potentially harmful to human health since it can lead to increased levels of toxins and bacterial development. Ammonia, nitrite, and nitrate are examples of nitrogen compounds that not only contribute to eutrophication but also can cause direct toxicity (Holeton et al., 2011). Eutrophication has been more widely studied in lakes since their growth rates are higher and more observable compared to rivers. However, planktonic, or suspended, algal biomass will grow along a river's course, but it will never reach nuisance concentrations in the upper portions of the river (Hilton et al., 2006). On the other hand, long retention durations, comparable to the range of lake retention times, are seen in large rivers and deep, impounded rivers and canals. These times are far longer than algal doubling times, allowing a significant biomass of phytoplankton to form in the middle and lower parts of the river.

As the United States and other nations have begun to use nutrient control in the management of streams, concerns over the eutrophication of streams have been raised and the need for nutrient limit criteria have been emphasized (Dodds & Welch, 2000). The U.S. Environmental Protection Agency (EPA) used nationwide data from the 1990s, to compare the predicted baseline nutrients to river surveys to estimate the level of enrichment in US streams (Dodds et al., 2009). These findings showed that over 90% of the US ecoregions went over median values of total nitrogen (TN), and have grown over time. The authors estimated an economic loss of $2.2 billion annually due to the eutrophication of freshwater sources in the US caused by drinking water purification costs, real estate values and expenditure for recovery of threatened and endangered species, among others.

• Aquatic Life

Ammonia is highly toxic to fish and the recommended limit for permitted ammonia discharge into water bodies is no more than 0.02 mg/I. Fish in the receiving water bodies are harmed by the 20–80 mg/l of ammonia-nitrogen found in the wastewater effluents by petroleum refineries (Fang et al., 1993). Fish kills in aquatic environments have also been linked to anthropogenic discharges with high nitrite concentrations (Camargo & Alonso, 2006). However, laboratory research has examined nitrite concentrations that directly poison aquatic animals, just like they did with ammonia. According to these findings, species found in saltwater are more resistant to nitrite toxicity than those found in freshwater, most likely as a result of chloride ions' ability to lessen aquatic creatures' tolerance (Lewis & Morris, 1986). After researching the reaction to the exposure of nitrite toxicity, some taxa of freshwater invertebrates and fish, such as salmonids and cyprinids, seem to be the most sensitive to nitrogenous compounds in water. These include decapods and amphipods, as well as certain insects and fish (Camargo & Alonso, 2006). While there is a dearth of research focused on the effects of nitrogen effluents from petrochemical industries on aquatic ecosystems, nitrogen pollution through nutrient loading from point and non-point sources in streams has been evaluated (Chambers et al., 2012, Dodds & Welch, 2000). A standing example of this is the creation of dead zones in the Gulf of Mexico caused by nitrogen runoff from farms in the Midwest, which has led to a depletion in fish stocks and their habitat resulting in an annual loss of $2.4 billion for over three decades (Union of Concerned Scientists, 2020). There is a need for similar studies targeting the impacts of untreated pollutants in wastewater from petrochemical refineries, specifically in ecologically vulnerable regions, to subsequently update appropriate ELGs in the United States for healthier and functional ecosystems.

2.6.1.2. Human Health Impacts

Humans, particularly infants, are most vulnerable to the impacts of nitrates and nitrites in drinking water. In the case of rivers and streams that provide a drinking water source to many communities and are associated with groundwater that chemicals leach into unless stricter effluent guidelines are established, nitrates and nitrogen-associated compounds pose a serious threat to the survival rate of infants and reproductive health of adults (de Vries, 2021). Manassaram et al., reviews the correlation between the presence and consumption of nitrates in drinking water to adverse reproductive and infant developmental outcomes (Manassaram et al., 2006). A study by Schmitz found that human miscarriages have been linked to methemoglobinemia, also called blue baby syndrome which impacts the delivery of oxygen by red blood cells to tissues and cells (Schmitz, 1961, Ward et al., 2018). According to a previous assessment of methemoglobin levels during pregnancy in women, the study concluded that elevated maternal methemoglobin levels were most commonly induced by nitrates and nitrites that led to miscarriages. Even while the nitrate concentration was below the regulated standards in drinking water, epidemiologic studies have shown an increased cancer risk among people who have consumed public water supplies with elevated nitrate levels for several decades (van Grinsven et al., 2006). Higher levels of nitrate in the public supply have been linked to increased risks for ovarian cancer, non-Hodgkin's lymphoma, and urinary bladder cancer (Weyer et al., 2001, Ward et al., 2001, Ward et al., 2003). An approximated 6 million people (2% of the total population) in the United States potentially consume polluted water that exceeds the World Health Organization (WHO) standard of 50 mg/l nitrate or the 3 mg/l nitrite standard (van Grinsven et al., 2006).

2.6.2. Selenium

2.6.2.1. Environmental Impacts

Selenium pollution can have a significant impact on humans, ecosystems and agriculture. Organic selenium compounds can be found in the environment as methylselenides, trimethylselenonium ions, or selenoamino acids (Pyrzynska,, 2002). Conversely, inorganic selenium compounds are found in the form of selenide, selenite, selenate and insoluble elemental selenium (Vesper et al., 2008) which can be found in wetlands, groundwater and surface waters. The main cause of the accumulation of selenium in the environment can be attributed to human activity. Industries like mining, power plants, and oil refining are some of the main sources of selenium discharge. However, it is important to note that selenium is essential for human health but, in excess, it can result in toxic effects. Problems associated with toxic levels of selenium are due to increased bioavailability and consumption. The discharge of untreated or inadequately treated wastewater containing high levels of selenium from mining, refinery, and power plant operations causes direct pollution of water bodies. (Li, et. al, 2022). The burning of fuels and coal containing selenium can result in air pollution. The fly ash resulting from the burning of such fuels can contaminate natural water bodies through precipitation and runoff. Furthermore, selenium pollutants in the soil may also seep into the groundwater, posing a risk to its quality. (Li, et. al, 2022).

2.6.2.2. Human Health Impacts

Although it is uncommon, exposure to elevated selenium levels can result in some negative symptoms in people, such as hypochromic anemia, leukopenia, and nail damage. Employees who produce selenium rectifiers are especially vulnerable to long-term hazards. Teeth mottling, vomiting, and diarrhea are just a few of the symptoms that can result from accidentally consuming selenium. Moreover, it may result in neurological problems such as convulsions, acroparesthesias, and weakness (Li, et. Al, 2022). Furthermore, selenium-contaminated water can build up in food chains and cause a variety of harmful effects on living organisms. This includes shortened life spans, stunted growth, decreased rates of reproduction, and weakened immune systems. (Li, et. al, 2022).

2.6.3. Nickel

2.6.3.1. Environmental Impacts

The primary contributors to the presence of heavy metals in water resources include industrial emissions, the extraction of metals, the improper application of chemical fertilizers and pesticides, and the concentration of heavy metals in the atmosphere (Khan et al., 2019a; Khan et al., 2019b; Khan et al., 2019c; Khan et al., 2023). Nickel plays a crucial role in the metabolic processes of plants, yet it becomes harmful to most plants at high concentrations (Ahmad et al., 2023). It impacts several enzymes that are vital for a range of metabolic activities, including those that regulate the digestion and mobilization of nutrients in seeds. Conversely, a lack of nickel can adversely affect plant growth and development in numerous ways, including the disruption of nitrogen metabolism and acceleration of plant aging (Alloway, 1995). Elevated levels of nickel in the soil can substantially reduce the germination rate of seeds across various crops. Additionally, during the vegetative growth phase, high nickel concentrations can decelerate the growth of shoots and roots, impair branch development, and cause alterations in the morphology and some physiological functions of the plants (Rothenberg et al., 1994).

2.6.3.2. Human Health Impacts

Exposure to nickel can lead to a variety of adverse health effects, such as allergic reactions, issues with the kidneys and heart, lung fibrosis, and cancers of the lung and nasal passages. While the precise molecular processes behind nickel's harmful effects remain unclear, it is thought that disruptions in mitochondrial function and oxidative stress are key factors contributing to its toxicity (Ugulu, 2015a). There are no recommended levels for the essentiality or dietary intake of nickel for humans. Nickel can also cause genotoxic effects indirectly by interfering with DNA's repair mechanisms. It has been proposed that nickel's ability to inhibit DNA repair could lead to its accumulation in breast tissues, potentially leading to malignant tumors (Rothenberg et al., 1994). Thus, nickel and its compounds have been classified as Group-I carcinogens to humans. Nickel exposure has been found to reduce total erythrocyte count, hemoglobin levels, packed cell volume, and to increase the osmotic fragility of erythrocytes (Wojtala et al., 2014). It also blocks the absorption of iron, causing anemia (Gay & Gabicki, 2000), and reduces the thermostability and deformability of erythrocytes, as well as the rate at which they release oxygen (Sedlak & Lindsay, 1968).

2.7. Environmental Justice & Drinking Water Impacts

Environmental Justice (EJ) is deeply rooted in broader social justice themes, touching on aspects of distributive, procedural, and recognition justices, especially focusing on how environmental burdens disproportionately impact lower-income and marginalized communities (Becker, 2004; Schlosberg, 2007; U.S. Environmental Protection Agency, 2017). This perspective acknowledges the deep relevance of environmental issues to low-income individuals and groups, highlighting a nuanced understanding of environmentalism among these populations (Martinez-Alier, 1995; Anguelovski and Martinez-Alier, 2014; Cory and Rahman, 2009).

The Safe Drinking Water Act (SDWA) was enacted by the US Congress in 1974 with the aim of safeguarding public health through the regulation of the public drinking water supply in the nation, as noted by the U.S. Environmental Protection Agency in 2006 (U.S. Environmental Protection Agency, 2006a, U.S. Environmental Protection Agency, 2006b). The Act mandates the EPA to establish national health-protective standards and requires that public water systems adhere to these standards. In recent years, the enforcement of environmental laws has been complicated by growing concerns regarding environmental justice. Although the SDWA includes provisions for both civil and criminal penalties, formal sanctions are infrequently applied by states. More commonly, regulatory compliance is encouraged through informal measures such as warning letters, site visits, or phone calls to remind water suppliers of their legal responsibilities (Cory & Rahman, 2008).

Studies on environmental justice in terms of water and water quality in the U.S. have shown that factors such as socioeconomic status and race are highly positively correlated with both exposure to water pollution and with SDWA violations by companies (Switzer and Teodoro, 2018). Given this disproportionate vulnerability of specific communities to water pollution in general, we analyze exposure of various population segments to pollution downstream of refineries, including analysis of drinking water intakes in downstream basins.

3. METHODOLOGY

This study investigates both potential drivers of pollution as well as the impacts of the pollution on downstream communities. The methods for each are explained in sections 3.1 and 3.2 below.

3.1. EXPLORATORY ANALYSIS

3.1.1. Research Objective

The exploratory analysis sought to identify and examine possible factors that explain variation in pollution levels across oil refineries. After discussions with various experts, including our client, EIP, wastewater engineers, and others, we identified three variables that could potentially explain variation in pollution levels: the age of facility, state regulations and/or enforcement, and company policies and management.

3.1.2. Methodology

3.1.2.1 Variables

We used a database of 81 refineries within the U.S. that included data on their location, production capacity, age, and level of pollution of several pollutants from 2021. The data was collected from the EPA's Enforcement and Compliance History Online (ECHO) and ATTAINS databases. We examined three potential explanatory variables:

1. Age of refinery
2. State
3. Company

Ideally, we would have liked to use the age of the wastewater treatment technology rather than the age of the refinery, however, such data was not available.

While there is data on overall discharges and for a number of specific pollutants, we restricted our analysis to 3 different pollutants

1. Nitrogenous compounds
2. Selenium
3. Nickel

In terms of pollution levels, we examined three different indicators:

1. Load (total annual discharges)
2. Average Concentration (pollutant level per unit of wastewater discharged)
3. Load/Production Capacity (load per size of refinery)

The load represents the overall discharge of pollutants into waterways and is likely to be most highly correlated with overall environmental impacts. Concentration shows the intensity of the pollutant for each unit of wastewater discharged. The load/production capacity divides the load by the production capacity of the refinery in order to normalize for refinery size. Ideally, we would have liked to look at load per production (i.e., the wastewater pollutant levels per unit of oil refined); however, we did not have data on actual production levels, rather, only on production capacity, that is the maximum potential production levels. Nevertheless, this variable normalizes for refinery size, and should serve as a reasonable proxy for the pollution intensity relative to production output.

3.1.2.2 Analyses

In order to analyze the correlation between refinery age and pollution levels, we conducted liner regressions for each of the 3 pollutants using each of the 3 measures of pollution levels.

In order to evaluate the effect of state, we conducted boxplots and analysis of variance (ANOVA) tests on the difference between average levels for each of the 3 pollutants and pollution level measures, by state. We grouped states with less than 3 refineries into one category of “others”. We also looked at the locations of the top 10 most and less polluting refineries for each of the three pollutants and pollution levels in order to see if there were any obvious correlations between state and refinery pollution.

We conducted an identical analysis examining the variation across companies. For the analysis, those companies with less than 3 refineries were grouped together under the category “others”.

The analysis was conducted with RStudio.

3.2. GEOSPATIAL ANALYSIS

3.2.1. Research Objective

The geospatial analysis aims to identify and compile collective sociodemographic attributes of the downstream populations from each refinery. The database will prove useful in locating disproportionately affected communities, taking into consideration environmental justice issues pertaining to the discharge of pollutants in waterways. The correlations will help in understanding who will benefit most from updating the ELGs by EPA and where they are present.

3.2.2. Approach

ArcGIS Pro was utilized to create maps and construct models to measure the downstream impacts of the toxic pollutants on environmental justice communities. The subwatersheds, 12-digit Hydrological Unit Codes (HUC12s), encompassing downstream waterways that are being polluted were identified since they represent the potential area affected by contaminated water from the waterway. In addition, drinking water intake from surface water facilities for downstream watershed units is included in the final database to identify potentially high costs of water purification and chemical compounds that are discharged into waterways without an updated limitation guideline. The final database (Appendix B) handed over to our client, EIP, will include the environmental justice characteristics of the disproportionately affected populations (in census block groups) residing 10 miles downstream of point locations of outfalls that will be utilized to perform the analysis to identify waterways these refineries pollute. All the data were projected to the WGS 1984 coordinate system for consistency of the analyses.

3.2.3. Data

The primary data used in the analysis include the Environmental Protection Agency’s EJScreen data, which contains sociodemographic attributes of populations on the census block group level, which the analysis uses. The EPA EJScreen data is constantly updated, and the dataset used in our analysis was created in June 2023 and updated in September 2023. Data from EJScreen was chosen, as opposed to Census Bureau data and the Climate and Economic Justice Screening Tool since the EJScreen Tool contained calculated metrics for demographic indices and supplemental indices for different environmental factors and concerns. Specifically, the national Demographic

Index for census block groups were found to be the ideal indicator for measuring vulnerability of a downstream community. The EJScreen defines Demographic Index as “the average of two socioeconomic indicators; low-income and people of color.” Additionally, census block group level data on total population, children under the age of 5, senior citizens over the age of 64, low income, people of color, limited English-speaking households, less than high school education and unemployed numbers were included in the analysis for the final database, found in Appendix B.

The 12-digit Hydrological Unit Codes subwatersheds created by the United States Geological Survey (USGS) was used to identify the affected communities on a smaller scale and hence better accuracy.

A total of 81 refineries were identified by the client, that discharge the wastewater directly into the waterways in the United States with a total of 91 outfall points (since larger refineries have multiple outfall points). Some refineries had multiple outfalls, and they were reduced to one for the ease of analysis since the locations are in close proximity. After cleaning up the database of 81 refineries and removing invalid location coordinates, a total of 77 refineries were selected to perform the downstream analysis. The client has assembled background and pollutant discharge data as well as information about the current status of EPA deliberations and monitoring. The outfall points of petrochemical refinery were also provided by the client, and the dataset was cleaned to exclude incorrectly georeferenced locations.

Name	Source	Date	Link
Drinking Water Intakes per HUC12	EPA	Item created 08/27/2021	https://epa.maps.arcgis.com/home/item.html?id=883ff965258e4c1aabb40e842ef2cc2e
National EJScreen Data at the Block Group Level	EPA EJScreen	Released in June 2023, but updated in September 2023	https://www.epa.gov/ejscreen/download-ejscreen-data
Outfalls (92 points)	Environmental Integrity Project (EIP, client)		Client provided shapefile
USA Rivers and Streams	ESRI Data and Maps	Data updated 02/06/2020	https://hub.arcgis.com/datasets/esri::usa-rivers-and-streams/about
National watershed boundary (HUC12) dataset for the United States	USGS	Item updated 09/11/2023	https://dukeuniv.maps.arcgis.com/home/item.html?id=b60aa1d756b245cf9db03a92254af878

***Table 4**: Data Sources for Geospatial Analysis*

3.2.4. Assumptions

The analysis makes assumptions and considerations to ensure the results are informed and as accurate as possible and are as follows:

- Since the sociodemographic data is present as census block groups, we assume the population and characteristics are uniform throughout the block group.
- The census block groups that spatially intersect with HUC 12 subwatersheds are considered to be most affected by polluted or impaired waters since it is in assumption that populations of those block groups drink, swim, or access the waterways more significantly than ones that are inland or away from the waterbody.

- For the analysis, the carrying capacity and volume of the waterway are not taken into account. Further studies can indicate the increased or decreased impacts of pollutants depending on the size of the waterway.
- The block groups present 10 miles downstream of the outfalls and on the banks of the waterbodies were deemed most affected by the effluent discharges by the refineries.
- Outfall locations that were present near or in a lake, sea or the ocean do not have downstream characteristics. For such outfalls, a 3-mile radius was taken to identify the affected census block groups.
- The downstream feature is the path that a waterway would take, if it had the volume of water to flow, until the ocean from a specified point, here it’s the outfall.
- The number of drinking water intake sources from surface water for several HUCs were included. An assumption is made that the census block groups that fall within the respective HUCs consume the drinking water from those specified sources.

3.2.5. Analysis

The general workflow of the analysis is represented below in Figure 1.

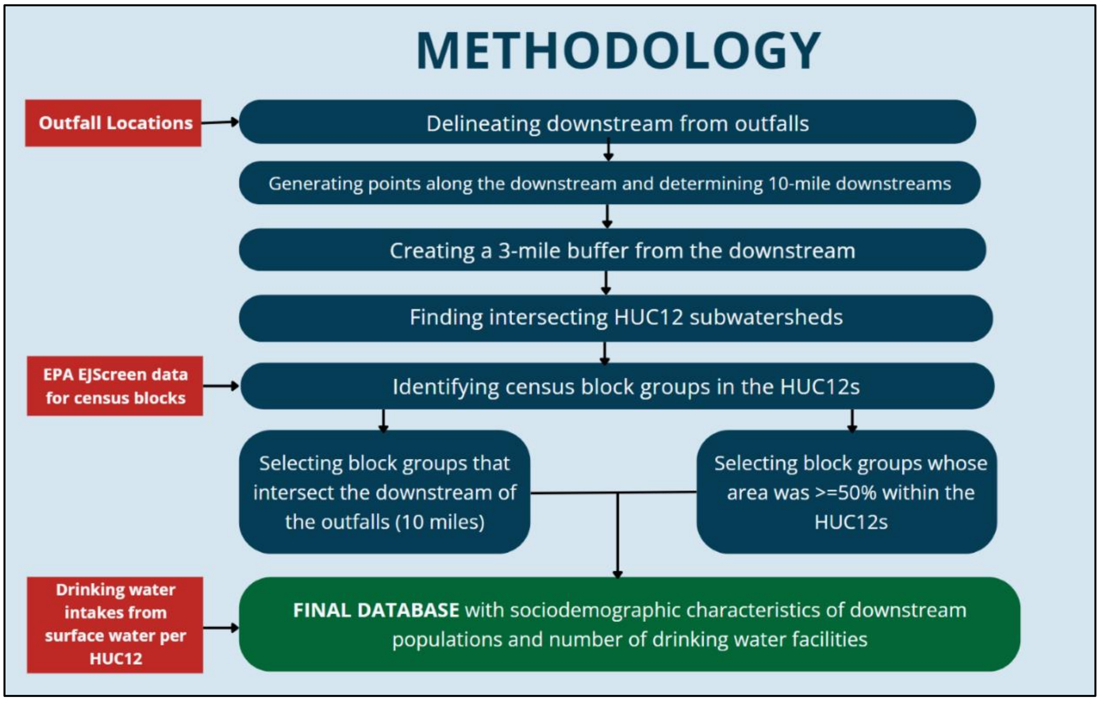


Fig 1. *Geospatial Analysis Model Workflow*

i. *Identifying Downstream*

The refineries (77 in total) were chosen to represent effluent discharge locations from the petrochemical refineries. To understand where the pollutants travel when discharged from the outfalls, identifying downstream features is crucial. The Trace Downstream tool was utilized to identify downstream from the outfall to the furthest downhill location, the ocean since it creates a hydrological database based on the 30m NHDPlusV2.1 for the continental United States, as seen in Figure 2. A 30-meter elevation resolution was chosen. For outfalls that are closer to each other, several overlapping downstream features were created, which can be considered as accumulative pollution from various refineries in the waterway.

Fig 2. *Refineries Discharging into US Waterways*

ii. *Identifying Downstream HUCs*

To determine the most affected HUCs, a 10-mile downstream segment from the outfall is considered. For this analysis, the Generate Points Along Lines tool was used to create points for every 10 US Survey Miles along the downstream features. The Split Line at Point tool was utilized to create 10-mile segments and the first 10-mile segment from every outfall was stored as the downstream feature for further analysis. To ensure that the 10-mile segments are consistent in length, some were manually selected to reach the 10-mile length. A buffer of 3 US Survey Miles was generated for the 10-mile downstream line features to select HUC12 subwatersheds that extend from the waterway, represented in Figure 3. For certain point locations that were present near lakes and on the coast that did not have a downstream, a radial buffer of 3 miles was considered.

The national watershed boundary constituting the HUC 12s dataset from USGS for the conterminous US was used. The HUC12 watersheds that spatially intersected with the buffered 10-mile downstream from the outfalls were selected as the potentially most affected watersheds.

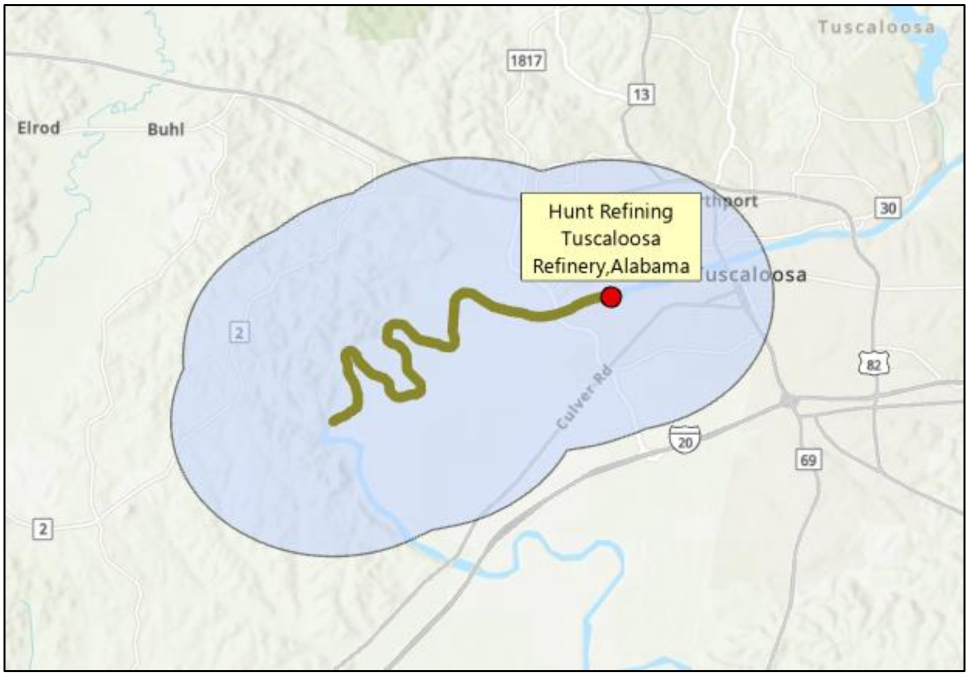


Fig 3. *Affected Downstream Area Sample*

iii. *Identifying Affected Census Block Groups*

The analysis assumes that the impaired waters pollute the subwatersheds and populations living in those HUC12s consume the water containing untreated pollutants from the refineries. The identified affected HUC12s were used to select census block groups that spatially fell within and around the subwatersheds. However, this selection included all block groups, irrespective of the percentage of area of the census block group that intersected with the HUC12.

To eliminate the block groups that do not significantly fall within the affected subwatershed boundaries, a negative buffer was composed to select census block groups that are within the 3-miles from the downstream segments. The negative buffer creates an inner buffer boundary that is used to select block groups that are present near the impaired waterways from outfalls.

Additionally, since the subwatersheds can be large in area, a spatial intersection leads to the selection of all block groups and most are further away from the affected waterways. To eliminate these block groups, they were intersected with the HUC12 boundaries and the block groups whose area was at least 50% within the subwatershed boundary were selected.

Finally, the census block groups present along the downstream buffer and the ones whose area fell significantly within the HUC12 were chosen to be the best representation of the significantly affected populations, which can be observed in Figure 4.

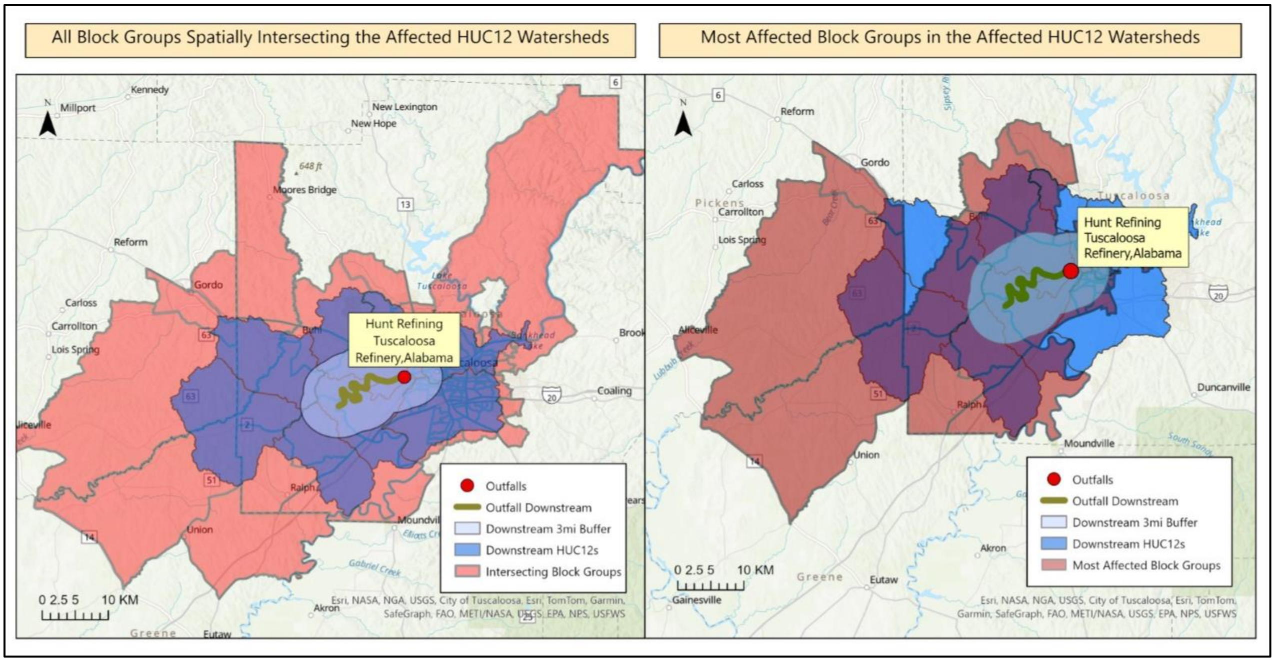


Fig 4. *Selecting Downstream Census Block Groups that are most affected*

iv. *Drinking Water Intake Facilities per HUC12*

Drinking water intake facilities from surface water per HUC12 data was extracted from a public database in ArcGIS Online. The HUC12s that intersected with the affected downstream watersheds were selected and combined into a single downstream watershed with the summed count of total drinking water intake facilities downstream from the individual refineries. The downstream drinking water facilities data were present for 54 of the 77 refineries. The total count was merged with the final database containing the sociodemographic attributes of downstream populations and can be accessed in Appendix B.

v. *Downstream Sociodemographic Attributes and Drinking Water Facility Counts*

The final table contains the total number of combined downstream attributes of the affected census block groups with total population (sum), children under the age of 5 (sum), senior citizens over the age of 64 (sum), low income (sum), people of color (sum), limited English-speaking households (sum), less than high school education (sum), unemployed (sum), Demographic Index (average), Supplemental Index (average), and drinking water facilities (sum) for every refinery. Percentages of each sociodemographic attribute were calculated in proportion to the total population count.

3.3. TECHNOLOGIES REVIEW DATABASE

As mandated by the Clean Water Act to adopt Effluent Limitation Guidelines (ELGs) based on the Best Available Technologies (BATs) available for the petrochemical refining industry, the ELGs do not reflect the advancement in modern technologies since 1985, when the ELGs were last updated. To provide a sample of existing and modern technologies that are available in the market to be implemented by refinery companies, a database with recent technologies for the target pollutants ammonia, selenium and nickel were compiled. This will support the client's advocacy in pointing at and acknowledging the variety of economically feasible options that the ELGs would be updated to implement and recommend them to refineries to adopt. The database can be utilized as a living document and as a starting point to keep track of modern technologies.

4. RESULTS & DISCUSSION

4.1. Exploratory Analysis

In this section, we present the results for Nickel as an example for the exploratory analysis investigating the variation in pollution discharges. The results of three target pollutants (nickel, nitrogenous compounds, selenium) were similar. The results for all pollutants are presented in the Appendix.

4.1.1. Age of facility and pollution levels

There is wide variation in the age of the refineries, with some dating back over a century. Load and load/capacity both tended to increase with age, while concentration decreased with age. A similar trend was found for the other target pollutants. This seems to indicate that newer refineries have invested in efficiency improvements. However, most of the observations were close the X-axis, and the trend lines were largely affected by the outliers (All of the R^2 lower than 0.1, with p-value all over 0.2). As a result, the age of facility cannot be seen as a very reliable variable to explain the changes in pollution levels.

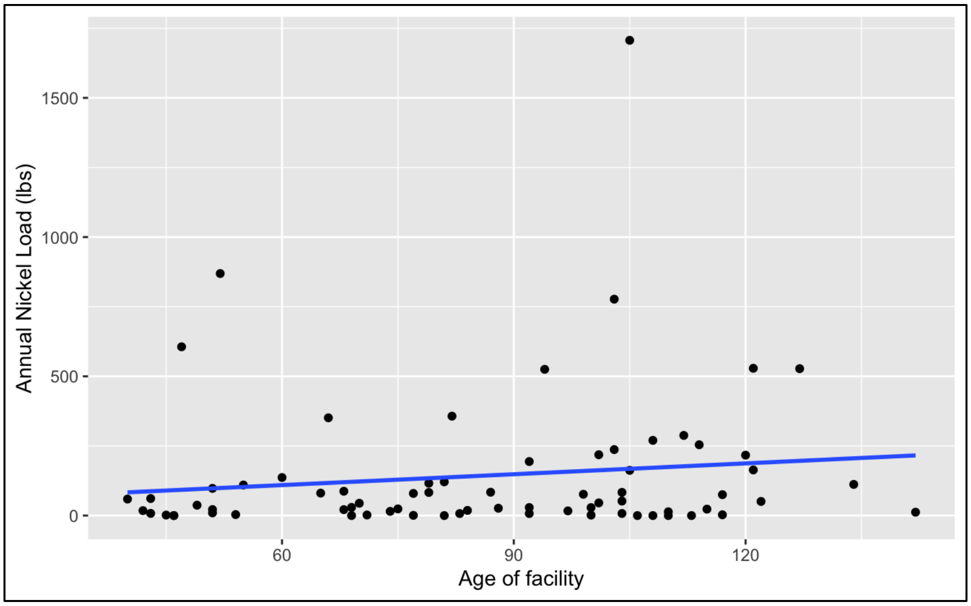


Fig 5. *Annual nickel load by age of facility (in years)*

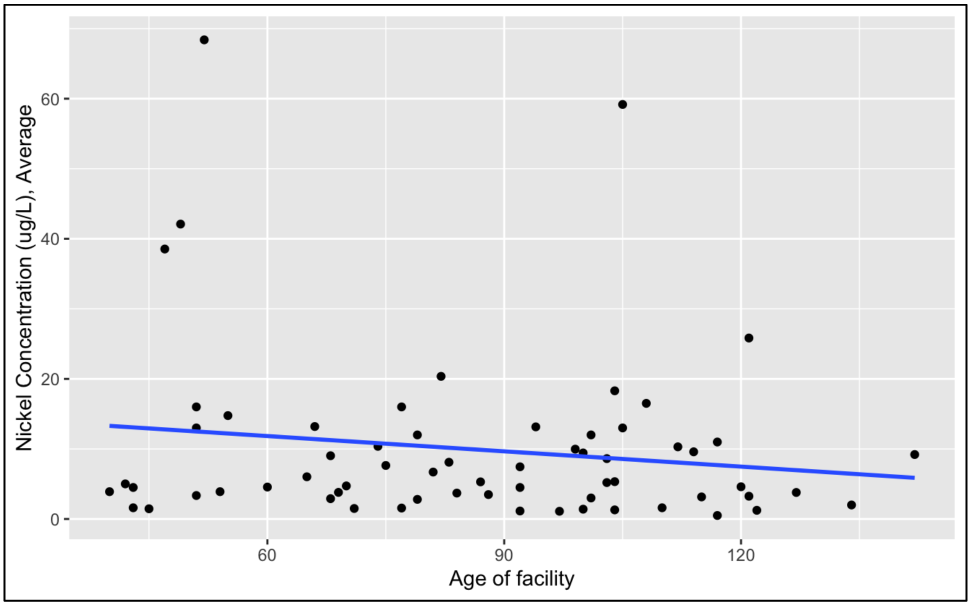


Fig 6. *Average nickel concentration by age of facility (in years)*

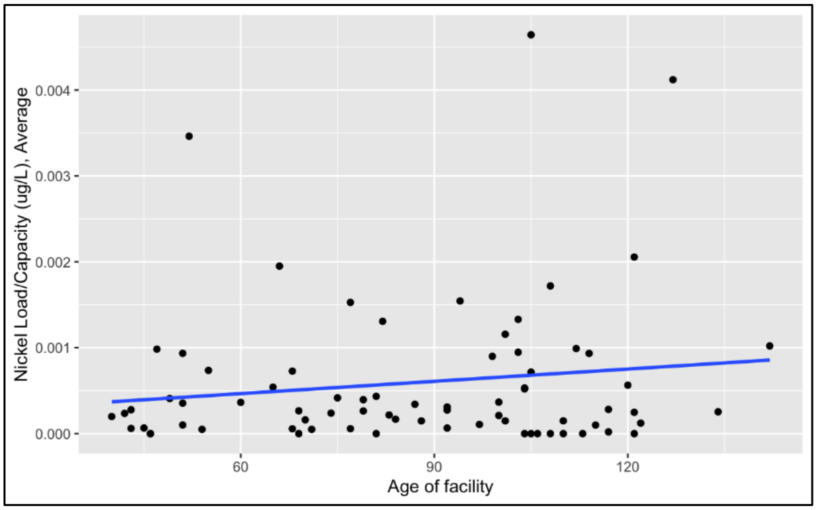


Fig 7. *Nickel load / capacity by age of facility (in years)*

4.1.2. States and pollution levels

There are some variations in different states, which California and Illinois have relatively higher average pollution levels than other states. Load (F-value = 2.6695, p-value < 0.05), concentration (F-value = 1.5278, p-value = 0.1708), and load/capacity (F-value = 3.0244, p-value < 0.01) all have similar variations. This seems to indicate that the changes in environmental policies and regulations in states could affect the pollution level. The difference in discharge concentration is not as significant as load and load/capacity since it the main indicator for the environmental policies and regulations.

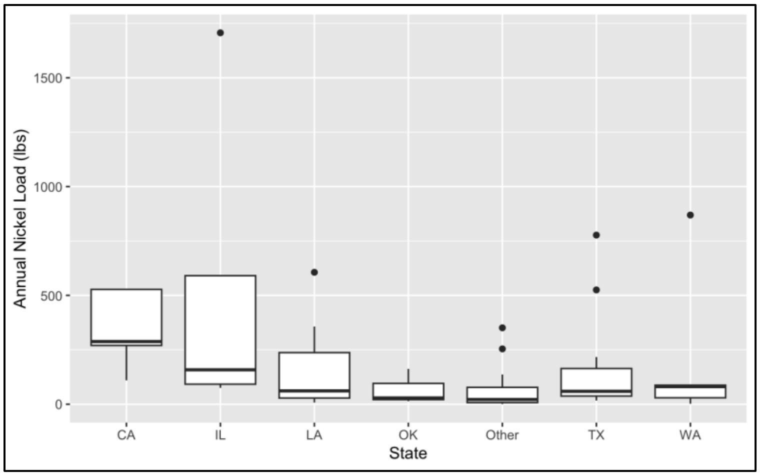


Fig 8. *Annual nickel load by states.*

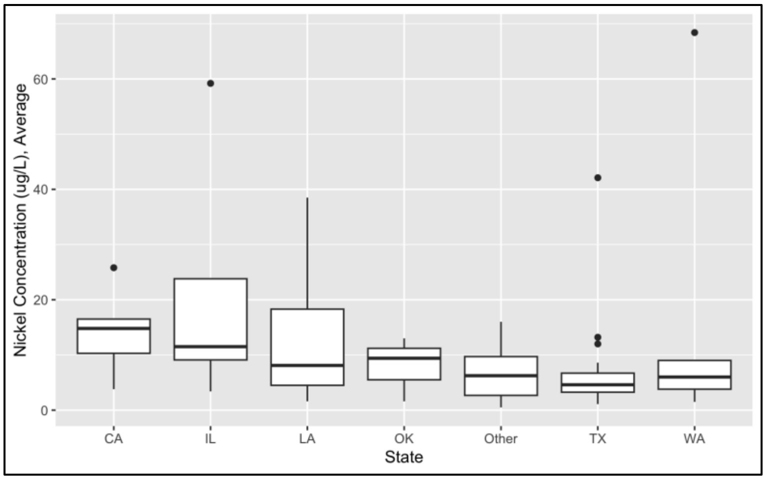


Fig 9. *Average nickel concentration by states.*

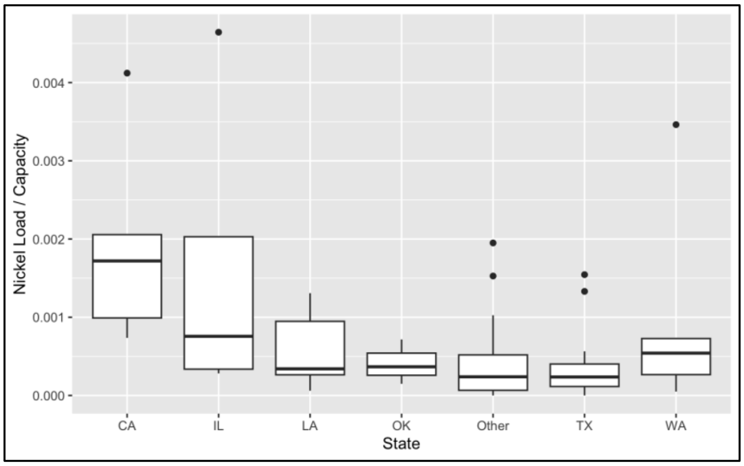


Fig 10. *Nickel load / capacity ratio by states.*

4.1.3. Companies and pollution levels

There are some differences between companies, with companies such as ExxonMobil, Chevron, PBF and Philips 66 having relatively higher average pollution levels. PBF and Philips 66 are the top two companies in terms of pollution loads. Load (F-value = 3.5324, p-value < 0.05) and load/capacity (F-value = 2.2783 p-value < 0.05) have more significant variation compared to discharge concentration ((F-value = 0.4394, p-value = 0.8952). The results were similar for all three of our target pollutants. This seems to indicate that there is reason to believe that corporate management or policies, including investment in wastewater treatment may explain some of the differences in pollution levels. However, such variation may also be due to differences caused by slightly different products produced by different companies.

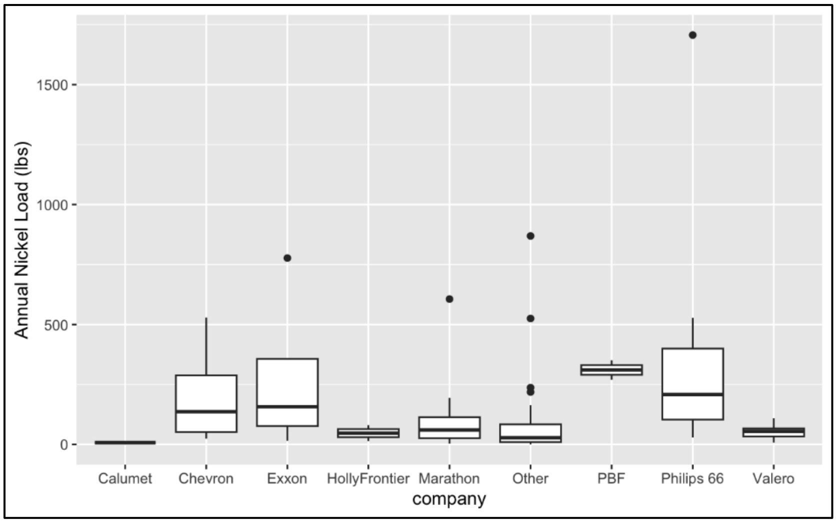


Fig 11. *Annual nickel load by companies.*

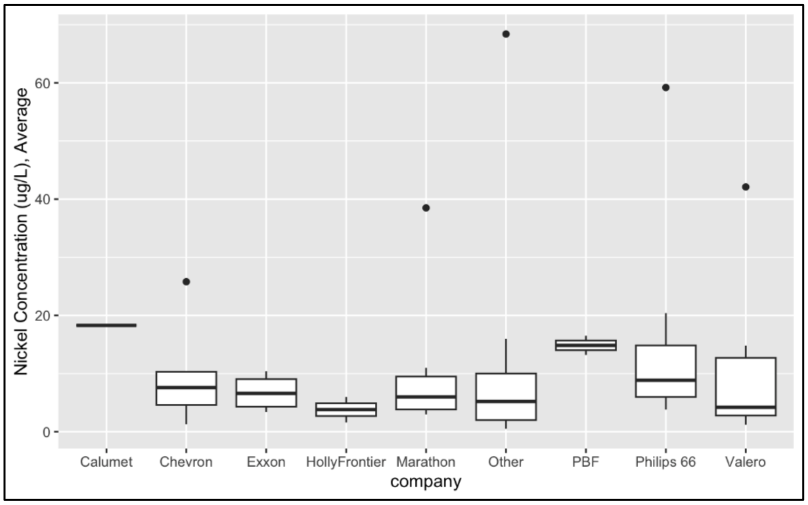


Fig 12. *Average nickel concentration by companies.*

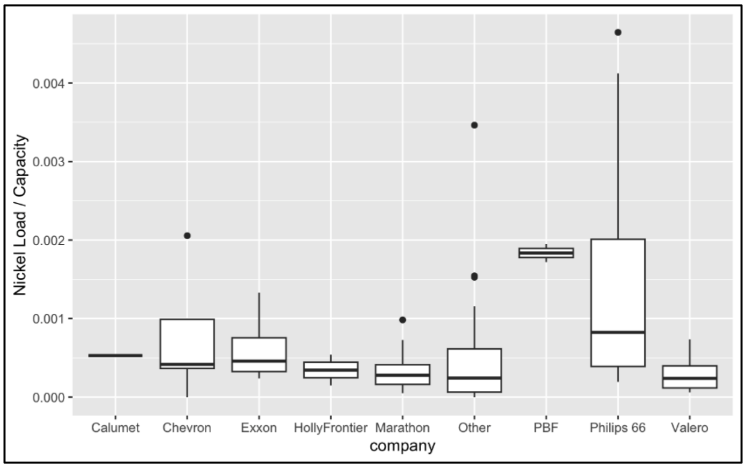


Fig 13. *Nickel load / capacity ratio by companies.*

4.1.4. Best and Worst Performances by companies

From the former exploratory analysis, state and company are two variables that could affect the pollution levels significantly. However, there some conflicts in the illustration of most and least polluting refineries. The possible explanation for these conflicts might be the different products and production capacity in each refinery, even though the refineries are in the same state or belong to same company.

Top 10 Most Polluting by Load

Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Annual Nickel Load (lbs)
Phillips 66 Wood River Refinery	Wood River	IL	367,500	1,706.6
BP Cherry Point Refinery	Ferndale	WA	251,000	869.1
ExxonMobil Baytown Refinery	Baytown	TX	584,000	777.0
Marathon Garyville Refinery	Garyville	LA	616,000	606.0
Chevron Richmond Refinery	Richmond	CA	257,200	528.8
Phillips 66 Rodeo Refinery	Rodeo	CA	128,000	527.5
Pemex Deer Park Refinery	Deer Park	TX	340,000	525.1
Phillips 66 Lake Charles Refinery	Westlake	LA	273,000	357.0
PBF Delaware City Refinery	Delaware City	DE	180,000	351.0
Chevron El Segundo Refinery	El Segundo	CA	290,500	287.8

Table 5: *Top 10 Most Polluting by Load.*

Top 10 Least Polluting by Load

Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Annual Nickel Load (lbs)
Valero Meraux Refinery	Meraux	LA	128,000	7.8
Calumet Cotton Valley Refinery	Cotton Valley	LA	14,000	7.4
Suncor Energy Commerce City Refinery	Commerce City West	CO	111700	7.3
CountryMark Mount Vernon Refinery	Mount Vernon	IN	33,400	7.2
Marathon Tesoro Kenai Refinery	Kenai	AK	72,000	3.6
CVR Coffeyville Refinery	Coffeyville	KS	136,000	2.8
Par Pacific Tacoma Refinery	Tacoma	WA	42,000	2.1
Ergon Vicksburg Refinery	Vicksburg	MS	27,300	1.8
Cross Oil Smackover Refinery	Smackover	AR	7,700	1.6
Hunt Southland Refinery	Sandersville	MS	12,500	0.7

Table 6: *Top 10 Least Polluting by Load*

Top 10 Least Polluting by Concentration

Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Nickel Concentration (ug/L), Average
Calcasieu Refining Lake Charles Refinery	Lake Charles	LA	137,000	Below Detection Level
PBF Chalmette Refinery	Chalmette	LA	197,000	Below Detection Level
PBF Paulsboro Refinery	Paulsboro	NJ	105,000	Below Detection Level
HollyFrontier Tulsa East Refinery	Tulsa East	OK	75,500	Below Detection Level
ExxonMobil Baton Rouge Refinery	Baton Rouge	LA	542,000	Below Detection Level
Calumet Shreveport Refinery	Shreveport	LA	60,000	Below Detection Level
Vertex Refining Saraland Refinery	Saraland	AL	90,600	Below Detection Level
Valero Ardmore Refinery	Ardmore	OK	88,000	Below Detection Level
Marathon Mandan Refinery	Mandan	ND	74,000	Below Detection Level
Delek Krotz Springs Refinery	Krotz Springs	LA	83,000	Below Detection Level

Table 7: *Top 10 Least Polluting by Concentration.*

Top 10 Most Polluting by Concentration

Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Nickel Concentration (ug/L), Average
BP Cherry Point Refinery	Ferndale	WA	251,000	68.4
Phillips 66 Wood River Refinery	Wood River	IL	367,500	59.2
Valero Three Rivers Refinery	Three Rivers	TX	91,000	42.1
Marathon Garyville Refinery	Garyville	LA	616,000	38.5
Chevron Richmond Refinery	Richmond	CA	257,200	25.8
Phillips 66 Lake Charles Refinery	Westlake	LA	273,000	20.4
Calumet Cotton Valley Refinery	Cotton Valley	LA	14,000	18.3
PBF Martinez Refinery	Martinez	CA	157,000	16.5
Hunt Refining Tuscaloosa Refinery	Tuscaloosa	AL	52,000	16.0
Par Hawaii Refinery	Ewa Beach	HI	95,000	16.0

Table 8: *Top 10 Most Polluting by Concentration.*

Top 10 Least Polluting by Load/Capacity					
Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Annual Nickel Load (lbs)	Annual Nickel Load (lbs)/Capacity
Calcasieu Refining Lake Charles Refinery	Lake Charles	LA	137,000	-	0.00
PBF Chalmette Refinery	Chalmette	LA	197,000	-	0.00
PBF Paulsboro Refinery	Paulsboro	NJ	105,000	-	0.00
HollyFrontier Tulsa East Refinery	Tulsa East	OK	75,500	-	0.00
ExxonMobil Baton Rouge Refinery	Baton Rouge	LA	542,000	-	0.00
Calumet Shreveport Refinery	Shreveport	LA	60,000	-	0.00
Vertex Refining Saraland Refinery	Saraland	AL	90,600	-	0.00
Valero Ardmore Refinery	Ardmore	OK	88,000	-	0.00
Marathon Mandan Refinery	Mandan	ND	74,000	-	0.00
Delek Krotz Springs Refinery	Krotz Springs	LA	83,000	-	0.00

Table 9: *Top 10 Least Polluting by Load/Capacity.*

Top 10 Most Polluting by Load/Capacity					
Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Annual Nickel Load (lbs)	Annual Nickel Load (lbs)/Capacity
Phillips 66 Wood River Refinery	Wood River	IL	367,500	1,706.6	4.68
BP Cherry Point Refinery	Ferndale	WA	251,000	869.1	2.38
ExxonMobil Baytown Refinery	Baytown	TX	584,000	777.0	2.13
Marathon Garyville Refinery	Garyville	LA	616,000	606.0	1.66
Chevron Richmond Refinery	Richmond	CA	257,200	528.8	1.45
Phillips 66 Rodeo Refinery	Rodeo	CA	128,000	527.5	1.45
Pemex Deer Park Refinery	Deer Park	TX	340,000	525.1	1.44
Phillips 66 Lake Charles Refinery	Westlake	LA	273,000	357.0	0.98
PBF Delaware City Refinery	Delaware City	DE	180,000	351.0	0.96
Chevron El Segundo Refinery	El Segundo	CA	290,500	287.8	0.79

Table 10: *Top 10 Most Polluting by Load/Capacity.*

4.2. GEOSPATIAL ANALYSIS

The consolidated final database (refer Appendix B) contains collective sociodemographic characteristics of the communities from all affected downstream block groups, along with the effluent discharge data of each refinery previously compiled by the client. Using the database, exploratory analysis resulted in preliminary results to identify the locations, states, and social variables that were potentially affected due to the lack of stringent effluent limitation guidelines (ELGs) implementation.

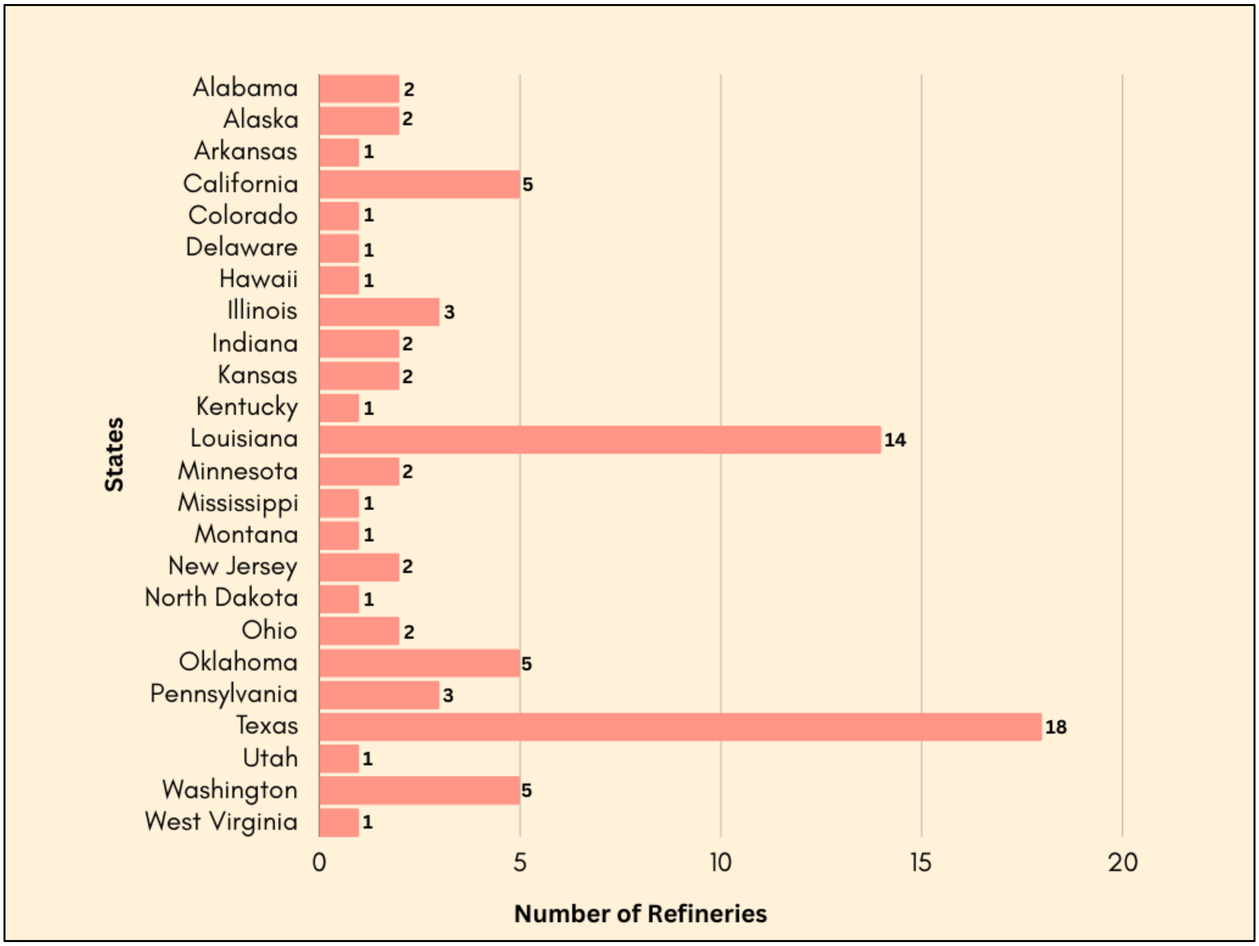


Fig 14. *Distribution of Refineries by State*

4.2.1. Assessing Location of Vulnerability of Downstream Communities

The Demographic Index, as defined by the EPA EJScreen, is an indicator of the vulnerability of a census block group based on the average of low-income and people of color. The average Demographic Index across all downstream census block groups downstream from each refinery was deemed to be the ideal indicator to use to measure social vulnerability. The higher the value of the index, the higher the social vulnerability of the residing population.

The average Demographic Index for the entire United States across all census block groups was 49.4. The Demographic Indices of the downstream communities of 56% of the refineries (43 in number) exceeded the average national value. This implies that more than half of all downstream communities are disproportionately affected by lack of stringent implementation of the ELGs. Additionally, the overall average Demographic Index of the downstream communities for the77 refineries was found to be 52, which also exceeds the national average. The top-ranking states with the highest average demographic index were identified to be Alabama, Texas, Colorado, Hawaii and Louisiana, in order of highest to lowest Demographic Index. Referring to Figures 14 and 15, we observe that Texas (18 in number) and Louisiana (14 in number) rank the highest in states having the greatest number of refineries discharging into US waterways.

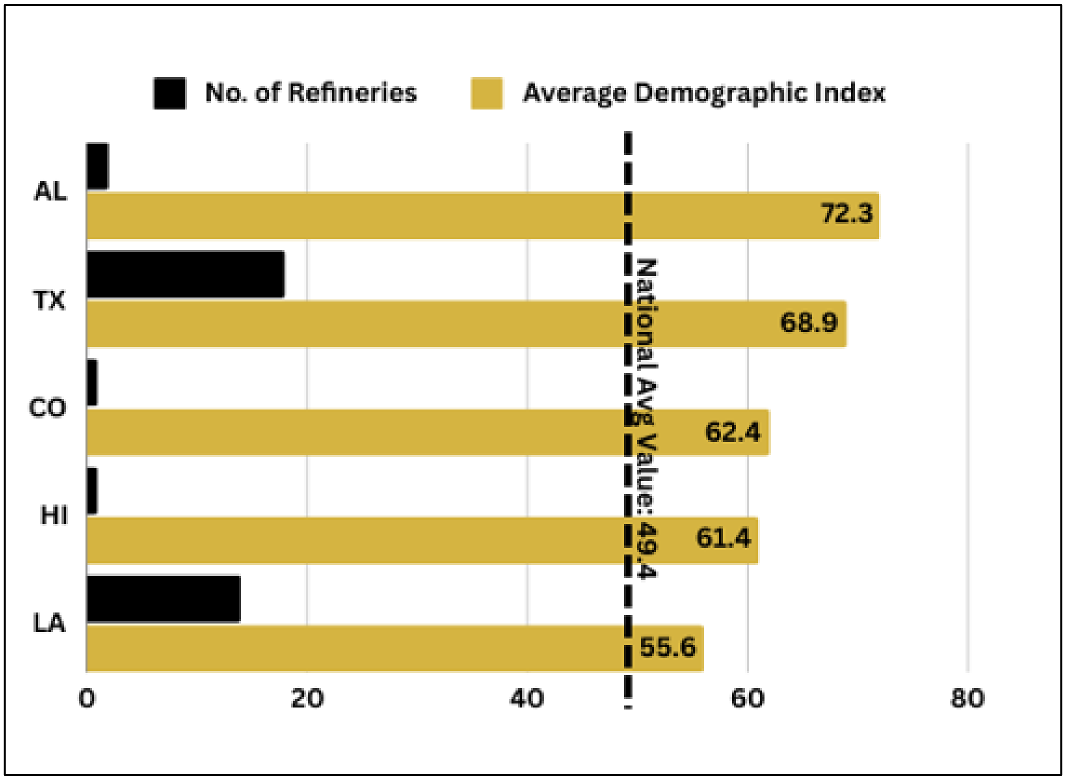


Fig 15. *States with the Highest Demographic Indices (Downstream)*

To analyze the most highly vulnerable downstream communities and where they are, we considered the 75th percentile of the average national Demographic Index, which was found to be 74.5. The 75th percentile of the average national Demographic Index being 74.5 can be interpreted as 75% of the census block groups evaluated have an index of 74.5 or lower, while 25% have a score higher than 74.5. The analysis yielded a total of 11 refineries that discharged into waterways upstream of the most highly vulnerable populations that exceeded the 75th percentile value. Of the 11 refineries, 9 were located in the state of Texas.

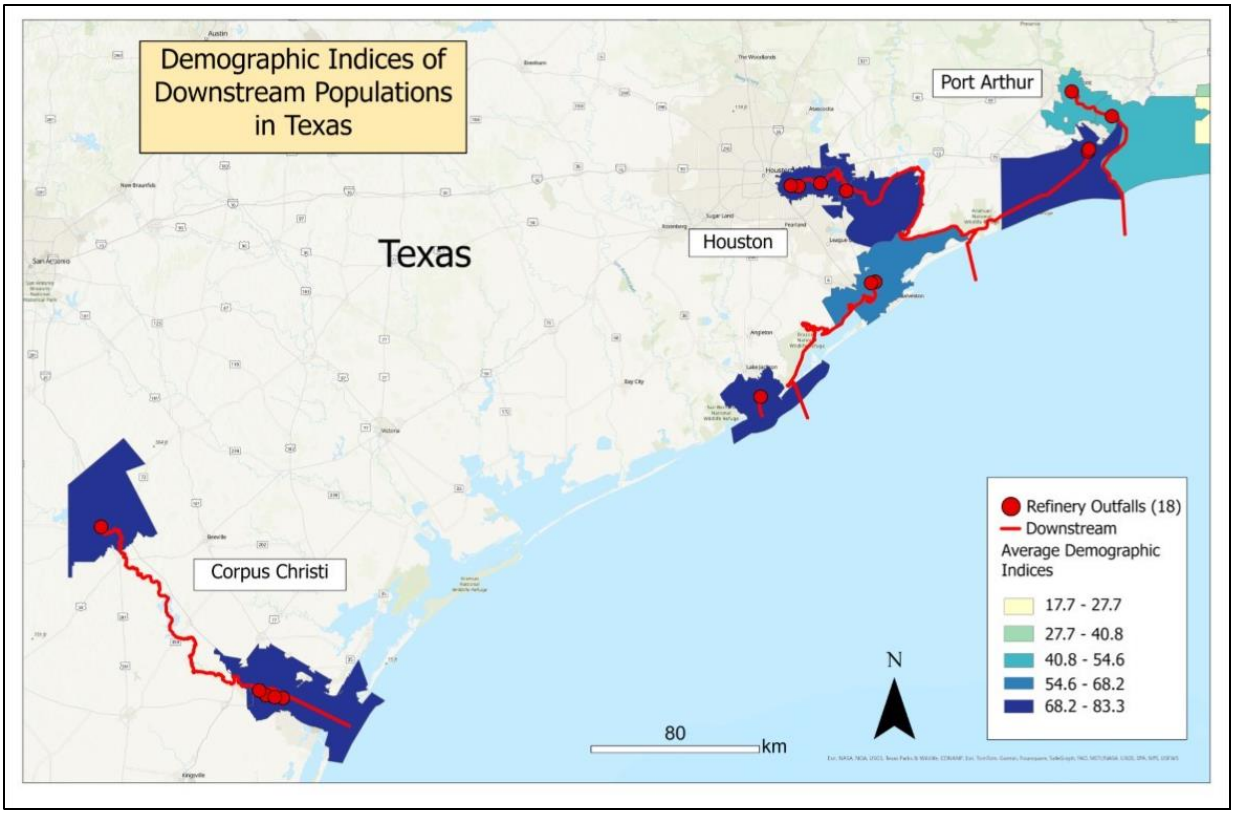


Fig 16. *Demographic Indices of Downstream Populations in Texas*

The downstream communities in the refineries in Texas are potentially most vulnerable to the effects of wastewater discharge from the petrochemical refining industries across the entire United States. For this reason, we chose to look at the subregions of Corpus Christi, Houston, and Port Arthur which have 5, 7, and 4 refineries respectively, represented in Figure 16.

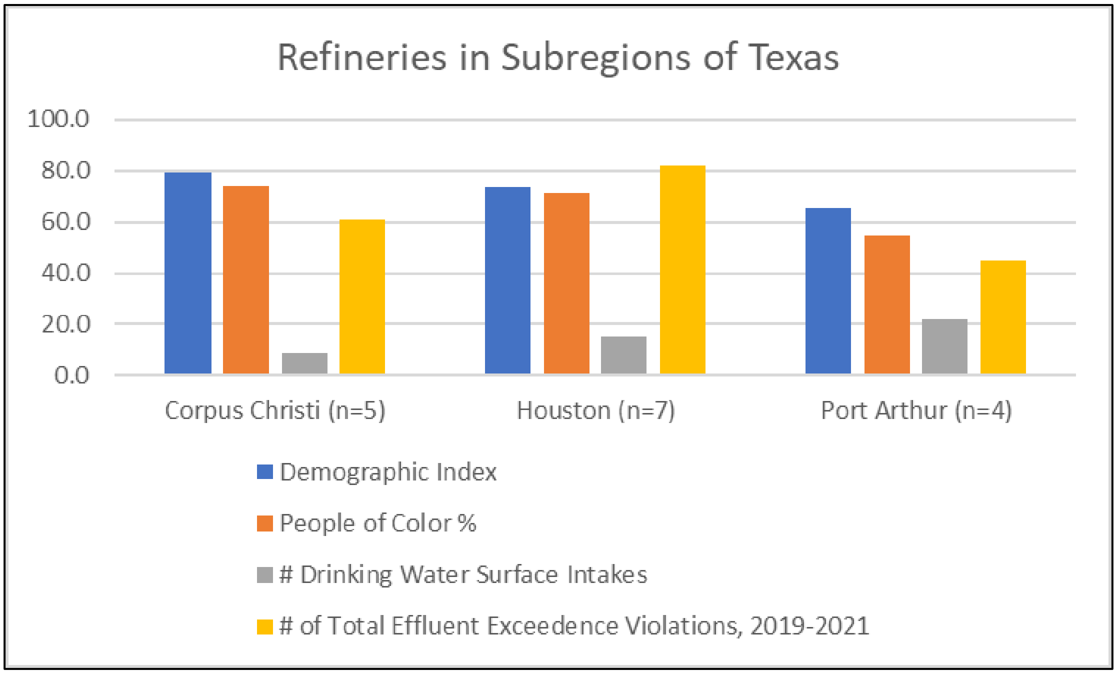


Fig 17. *Downstream Characteristics of Subregions in TX*

Observing the graphs in Figure 17, all three subregions are comprised of highly socially vulnerable populations with high average demographic indices, and Corpus Christi and Houston's are above the 75th percentile of the national average demographic index (Corpus Christi= 79.5, Houston= 73.6, Port Arthur= 65.4). Moreover, refineries in Corpus Christi and Houston pollute waterways upstream of large populations of people of color, clearly making this an environmental justice concern. Most of the refineries in these subregions faced multiple total exceedance violations in 2019-2021, with the refineries in Houston alone facing penalties for going over the designated permit limits 82 times. Stricter and higher penalties for violation need to be mandated to ensure compliance with NPDES agreements to prevent excessive pollutant discharge. A total of 46 drinking water surface intake facilities are present downstream from these subregions and need to be flagged as the most important to monitor toxin and chemical concentrations.

4.2.2. Identifying Impacts on Drinking Water

The pollutants in varying quantities, concentrations and chemical compositions are not strictly regulated by ELGs and hence have a high impact on downstream communities. The highly adverse effects are observed when untreated water is either directly or indirectly consumed by populations living downstream from these refineries. Drinking water intake facilities subject the water from waterways to physical, chemical and biological treatment prior to distributing them for public use.

However, with the lack of stringent pollutant limitations, the treatment facilities incur exponentially higher costs of treatment and potentially untreated chemicals that are not regulated by the Clean Water Act.

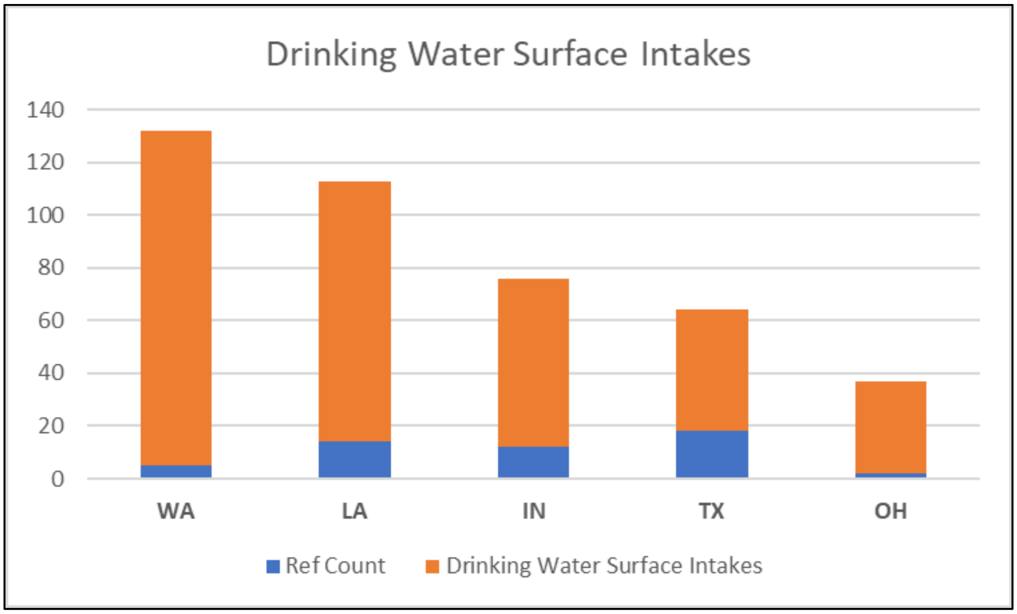


Fig 18. *States with the Highest Downstream Surface Water Intake Facilities*

The final database (found in Appendix B) includes data on the total number of drinking water surface intakes from downstream watersheds from certain refineries for which data was available (54 in number). From the data, we could analyze the states with the highest number of drinking water intake facilities downstream from the petrochemical refineries. The average percentage of children under the age of 5 residing in these downstream populations was 6.02%. The states of Washington (127 in number) and Louisiana (99 in number) ranked highest in the number of treatment facilities, as shown in Figure 18 and 19. Louisiana is a state of concern since it has 14 refineries discharging into waterways that comprise a very large number of drinking water treatment facilities.

However, we decided to focus on the state of Washington since the communities downstream of BP Cherry Point Refinery, WA, comprised the highest percentage of children under the age of 5. The average percentage of children in all the downstream communities of the 5 refineries discharging wastewater into the Salish Sea and Puget Sound was 5.8 %. We strongly believe that the detrimental human health effects of the pollutants, especially nitrogenous compounds like nitrates and nitrites, impact young children and infants in their early developmental stages and with lesser immunities (Schmitz, 1961). According to the pollutant effluent database provided by our client EIP, BP Cherry Point Refinery discharges 41,676 lbs of Nitrate-Nitrite as nitrogen into the waterway.

Washington state has increasingly fallen into the radar for increased levels of ‘forever chemicals’ known as PFAs and drinking water facilities face high treatment costs (Bernton & Villa, 2022). The origins of some of these chemicals in different parts of Washington remain ambiguous, while some are attributed to firefighting foams that were used decades ago. However, with the existing pressure on the public water supply system, higher costs of treatment are exacerbated by the lack of stringent standards on several wastewater pollutants. In addition, the state of Washington has not published the impairment status for its waterways for 2020 and 2022, making it difficult to understand the level of consequences of the petrochemical industrial discharge into potentially already polluted waters (Mohr, 2024). Moreover, the environmental effects can impact federally protected and ecoculturally significant species like the salmon that inhabit the waters of the Salish Sea and the Puget Sound.

Pollutants in wastewater discharge are oily and some are not regulated by the EPA-enforced limitation standards. State wastewater laws in Washington are enforced by the Department of Ecology, and they are frequently stricter than federal requirements. Even still, pollutants persist in the waterways and accumulate even under strict regulations. The Swinomish Tribe of the Pacific Northwest places great significance on pollution in Fidalgo Bay contributed by the two refineries in Anacortes-HollyFrontier Puget Sound Refinery and Marathon Anacortes Refinery. Elders from the Swinomish tribe place emphasize the ecological and cultural value of the waterways that provide a home to a variety of marine species, including clams, crabs, herring, and other marine life (Zane Gustafson, 2022). However, consumption of seafood from the Fidalgo Bay are known to result in cancerous and non-cancerous human health impacts according to a 2010 Washington Department of Health study (Washington State Department of Ecology, n.d.). Furthermore, Fidalgo Bay is now part of a toxics cleaning program run by the Washington Department of Ecology due to contamination from both past industry and refineries.

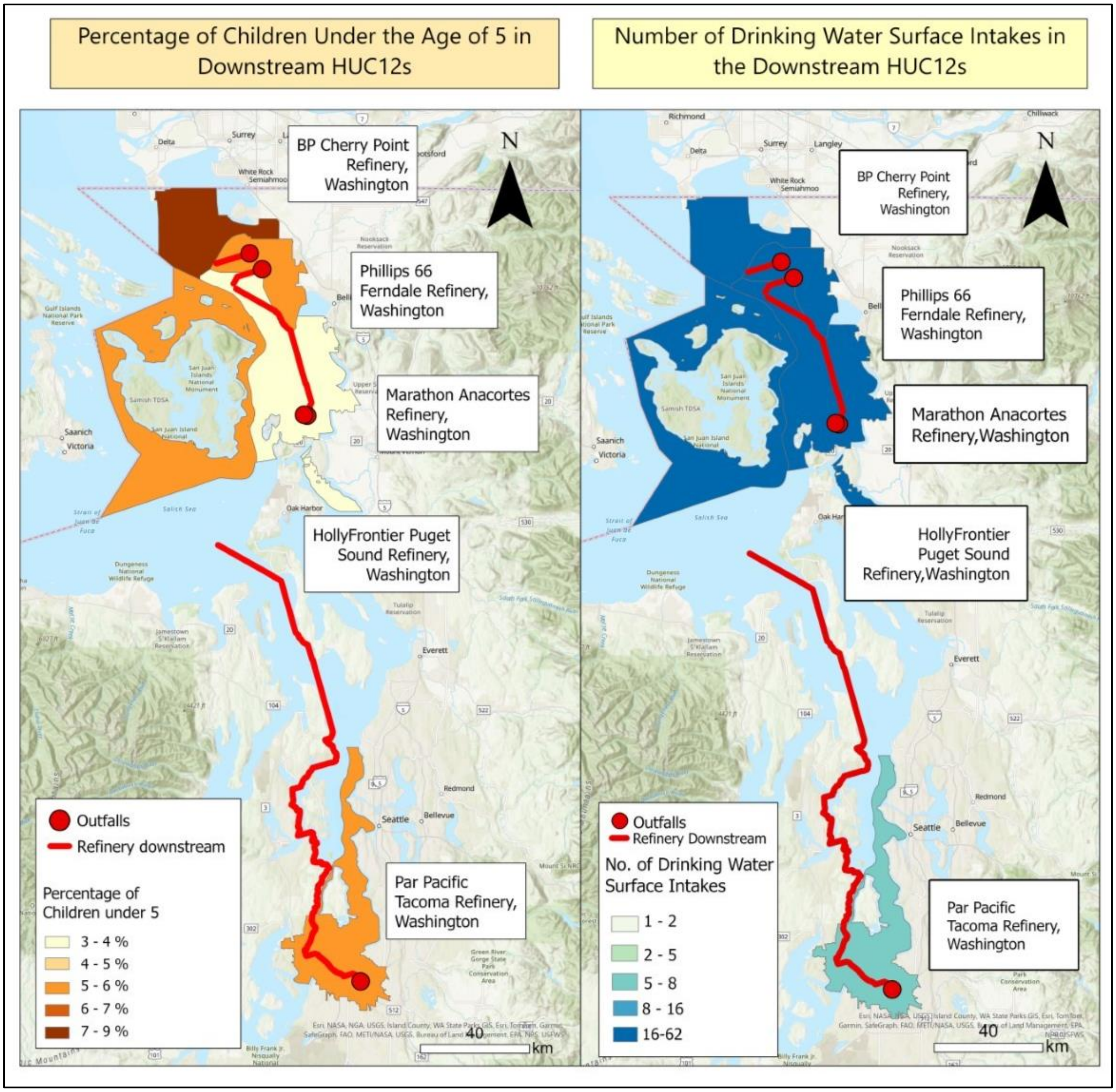


Fig 19. *Washington State Refineries and Downstream Characteristics*

4.2.3. Downstream Impacts by Suncor Refinery, Colorado

Repeated enforcement proceedings have been taken against Suncor Refinery in Colorado for violating the permit limits of its wastewater discharge and the limits of its air pollution emissions in addition to 28 oil spills within a decade (Peters, 2022). Sand Creek, the South Platte River, and groundwater have been contaminated for decades by the refinery by chemicals such as benzene, arsenic, heavy metals (cadmium, industrial and organic compounds), and PFAS (per- and poly-fluoroalkyl substances).

City	Commerce City West
State	CO
Demographic Index	**62.4**
People of Color %	**56.4**
Low Income %	27
Children Under 5 %	**6.9**
Senior Citizens %	9.3
No. of Drinking Water Surface Intakes	**5**

***Table 12**: Downstream Sociodemographic Characteristics of Suncor Refinery, CO*

The results of our analysis, in Table 5, showed that Suncor refinery was polluting waterways that flowed to vulnerable downstream populations that had a demographic index of 62.4 (national average demographic index = 49.4) who are disproportionately impacted. In addition, the downstream communities comprise approximately 7% children under the age of 5.

A family of "forever chemicals" created by humans, PFAS are hazardous in even extremely small amounts and difficult to decompose in the environment. The Colorado Department of Public Health and the Environment (CDPHE) proposed a revised wastewater permit that includes stricter limits for heavy metals like arsenic, and PFAS related to petroleum refining. However, the proposed permit does not provide protection against dangerous levels of water contamination, particularly from PFAS, for vulnerable communities that are already disproportionately affected. Children are more susceptible to the effects of PFAS because of their lower body weight, shorter lifespans during which toxic effects may appear, and growing organ systems (Woolf & Zajac, 2022). Reports from cities across the nation found PFAS in the drinking water as a result of the Environmental Protection Agency's (EPA) collaboration with state and local governments to monitor the concentration of particular PFAS compounds in municipal drinking water systems. The EPA increased its health recommendation standards for PFAS in drinking water in 2023, even though the health advisories are not legally binding. Five drinking water intake facilities were found downstream from the Suncor Energy refinery. Though the ELGs do not restrict PFAS and the refinery continues to discharge the toxic chemical into waterways, the updated standards of PFAS in drinking water have exponentially increased the cost of treatment for the drinking water facilities. In 2022, Colorado health officials funded additional testing for local water providers and discovered that several of them were testing above the new 4 parts per trillion EPA drinking water guideline (Booth, 2023). For this reason, extra steps of treatment by the consumer are necessary before consumption, which is achieved best by reverse osmosis systems for home filtration which is expensive and not affordable for everybody.

Communities of color in Denver already disproportionately face clean water injustice issues due to PFAs in the streams from fire-fighting foams used in the past (Tom I. Romero, II, 2022). In addition to the harmful chemicals, Suncor Energy was sued in court in 2018 by the Counties of San Miguel and Boulder and the City of Boulder in the state court for deceiving the public regarding their emissions and contribution to global warming due to the fossil fuel products they manufactured and sold (Doyle, 2022).

Based on the results we obtained from our analyses across different regions, sociodemographic characteristics, and drinking water impacts, we believe that certain vulnerable downstream communities would benefit the most from having the updated ELGs by the EPA. We ascertain that the states of Texas, Louisiana, Colorado, and Washington be the primary focus of advocacy for stricter pollutant regulations on the federal, state, and local levels of government. The Environmental Integrity Project can partner with local environmental and social justice advocacy groups to push for the use of modernized technologies and tighter chemical effluent limits based on the analyses.

5. STUDY LIMITATIONS & FUTURE RECOMMENDATIONS

Our study provides important insights into the potential impacts of harmful pollutants discharged by petrochemical refineries on environmental and human health. However, it is important to recognize several limitations that may introduce uncertainty and inaccuracies into our analysis. First, the lack of clear data regarding drinking water intake locations or supply sources makes it difficult to accurately evaluate exposure risks, as variations in pollutant levels in different water sources could significantly influence the results. Additionally, the inconsistency in units used to evaluate the volume of pollutants, such as selenium, discharge across scientific reports limits precise comparisons and may lead to inaccuracies in our assessments.

Moreover, our methodology relies on census block group data, which assumes uniform characteristics within each block group. However, this assumption may not be entirely accurate. This presumption represents the variability present within communities, leading to potential error in our analysis. Lastly, it is important to note that our study does not delve deeply into the screening methods employed by drinking water systems to detect pollutant contamination nor the potential impacts of drinking water contamination on public health. Therefore, further investigation into these critical aspects is warranted for a comprehensive understanding of the issue.

Moving forward, we recommend developing a tool based on the final database to identify environmental justice concerns downstream of point locations. A dashboard representing the different refinery locations along with the states, downstream population attributes of EJ populations, polluted waterways, and the number of drinking water locations can be created for visual aid. We recommend using the technology review as a living document and building a database of technologies being used to mitigate toxic pollutants to refer to when lobbying against the EPA. Lastly, attempting to locate the water systems and subsequently, the drinking water treatment facilities downstream from the refineries and contact them to understand the potential challenges faced will prove the strongest to advocate for updating the ELGs.

6. CONCLUSIONS

In conclusion, our analysis highlights the need for updated pollution control standards enforced by the Clean Water Act, particularly concerning pollutant discharged from oil refineries. Despite the Act's ambitious goal of ensuring that the quality of our nation’s waters would be safe by 1985, significant challenges persist. On reason is due to the discharge of wastewater by petrochemical refineries into waterways, which have continued to expand in capacity over recent decades. The effluent limit guidelines (ELGs) set by the EPA to address pollutant released from refineries have not been revised since 1985, failing to reflect advancements in wastewater treatment technologies. This lack of revision poses a significant risk to public health and the environment, as pollutants continue to harm downstream populations. Our research aims to address these shortcomings by providing robust evidence to support advocacy efforts led by our client, the Environmental Integrity Project. All in all, we identify modern wastewater treatment technologies used by oil refineries, examine potential influencing variable on pollution discharge, and evaluate the communities disproportionately impacted by refinery pollutants. By highlighting the urgent need for updated standards and effective enforcement by the EPA and all governing agencies alike, our study intends to contribute to the improvement of water quality and the protection of environmental and human health.

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Appendix A – Review of Modernized Treatment Technologies

This appendix contains a table of modern technologies used to reduce the volume of pollutants discharged in to our nation’s waters. The table specifically reviews recent treatment technologies for Nitrogen, Selenium and Nickel.

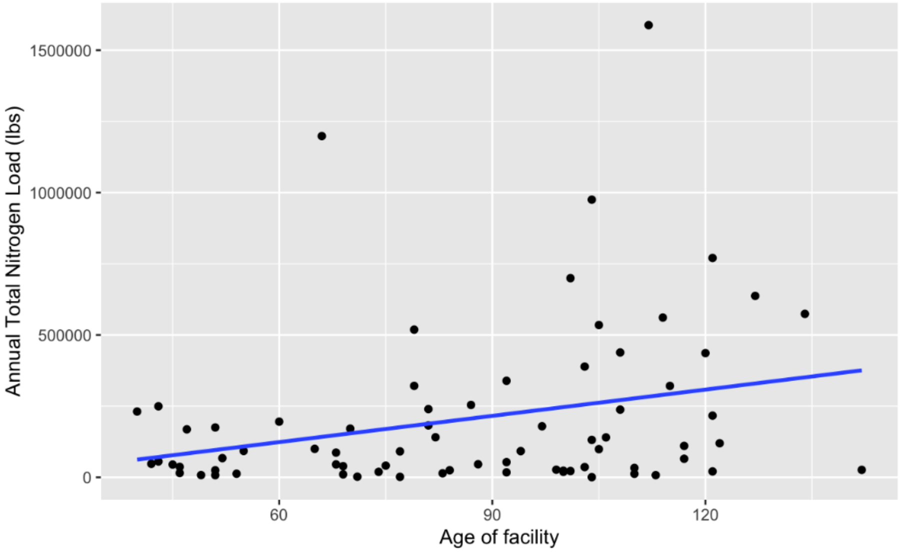
Appendix B – Graphs and tables of exploratory analysis

This appendix contains the tables for most and least polluting table for the three target pollutants (Nickel, Selenium, and Nitrogenous compounds), and the graphs about the difference in age of facilities, state, and company, including the results of R square and F-test.

i. Nitrogenous Compounds

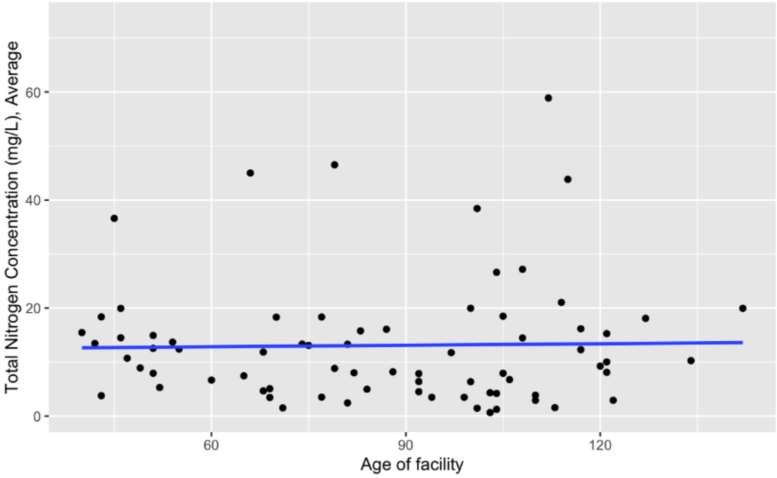
- **By age of facility**

The Load of Nitrogenous compounds changes by age of facility



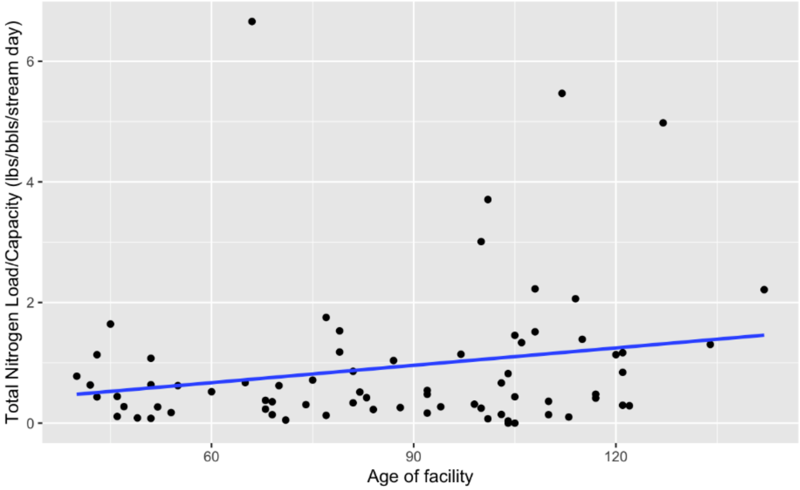
R^2 = 0.06515, p-value = 0.01662

The Concentration of Nitrogenous compounds changes by age of facility



$R^2 = 0.06515$, p-value = 0.01662

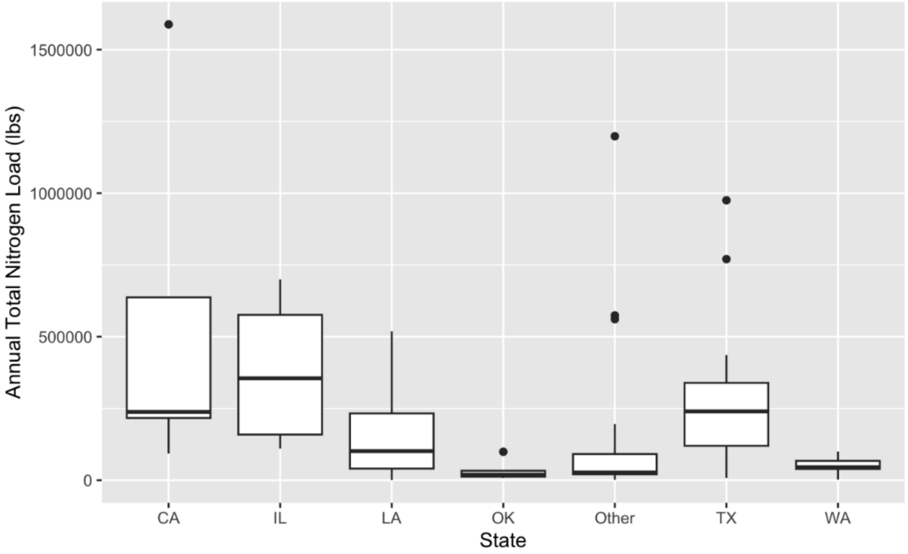
The Load / Capacity of Nitrogenous compounds changes by age of facility



$R^2 = 0.653$, p-value < 0.01

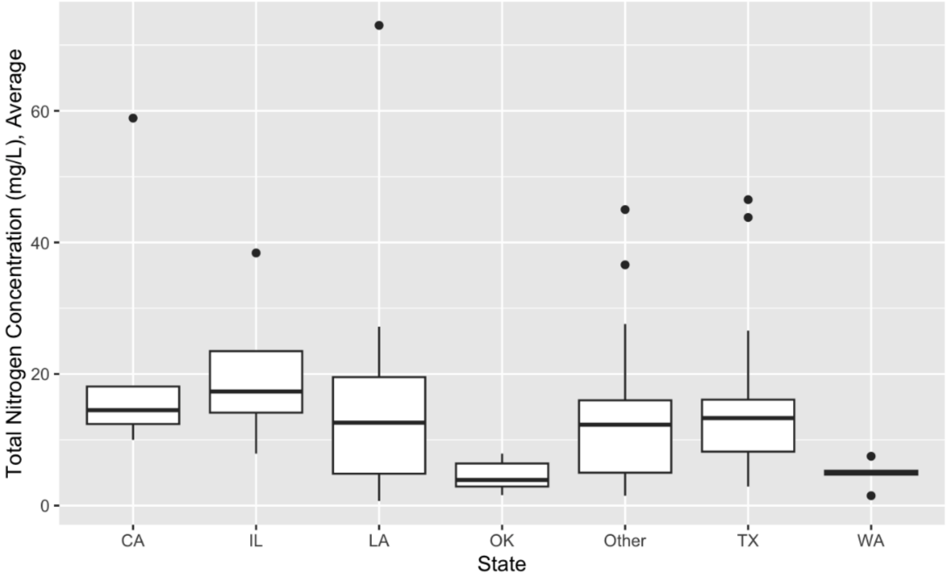
- **By state**

The Load of Nitrogenous compounds changes by state



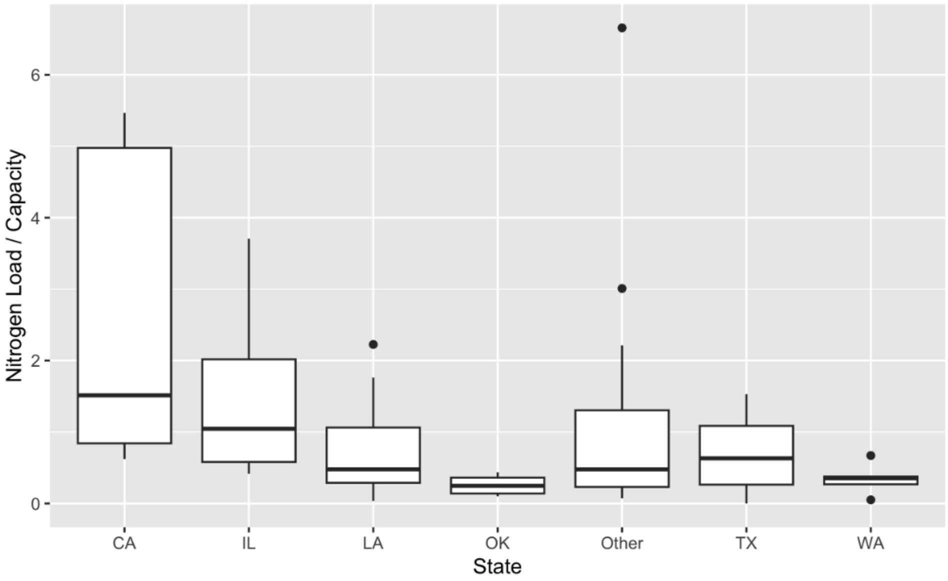
F-value = 3.178, p-value = 0.008

The Concentration of Nitrogenous compounds changes by state



F-value = 1.545, p-value = 0.176

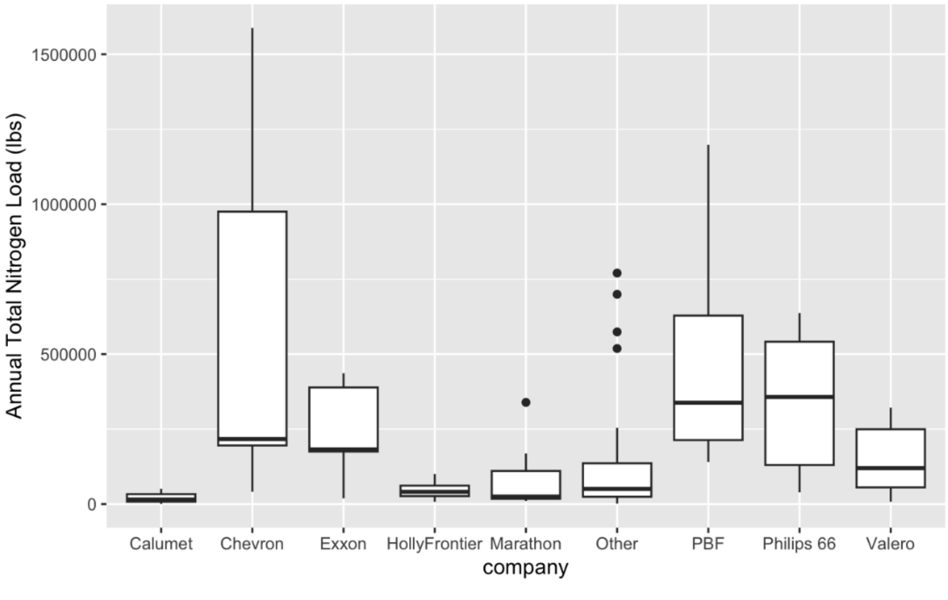
The Load / Capacity of Nitrogenous compounds changes by state



F-value = 3.204, p-value = 0.0075

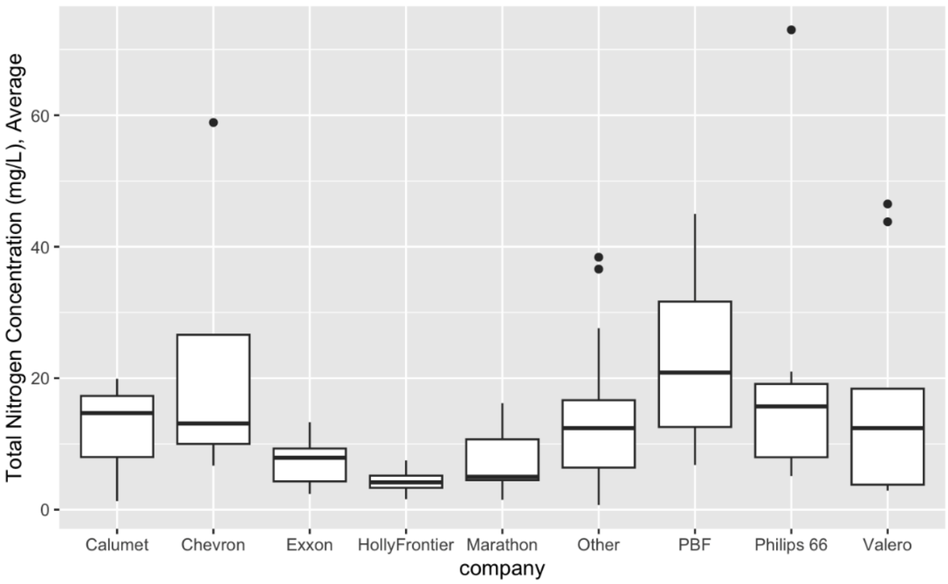
- **By company**

The Load of Nitrogenous compounds changes by company



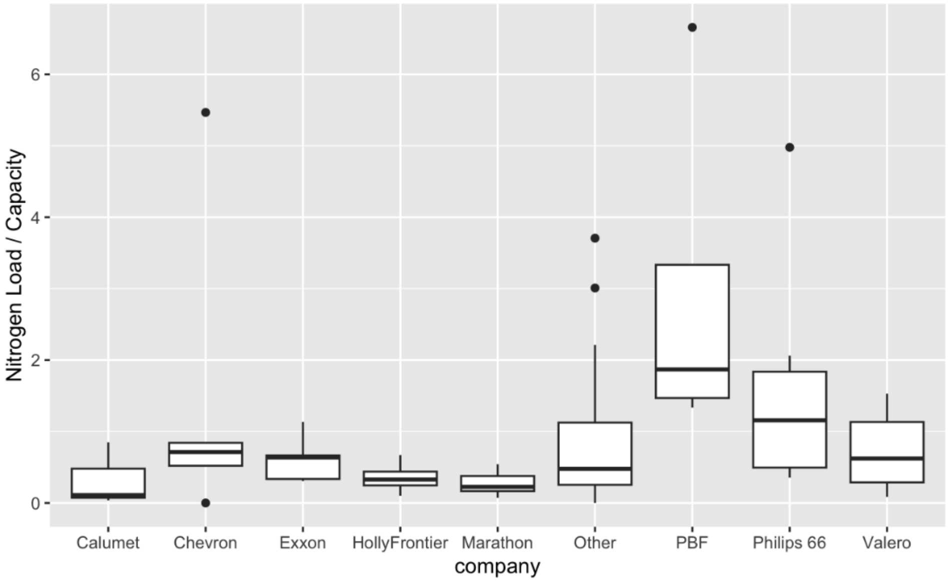
F-value = 3.532, p-value = 0.174

The Concentration of Nitrogenous compounds changes by company



F-value = 1.699, p-value = 0.114

The Load / Capacity of Nitrogenous compounds changes by company

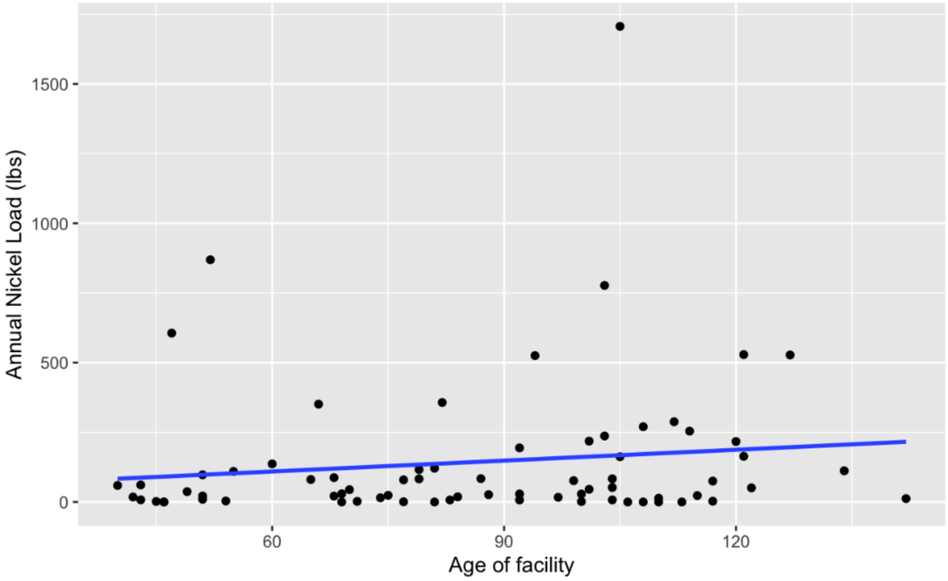


F-value = 3.125, p-value = 0.00436

ii. Nickel

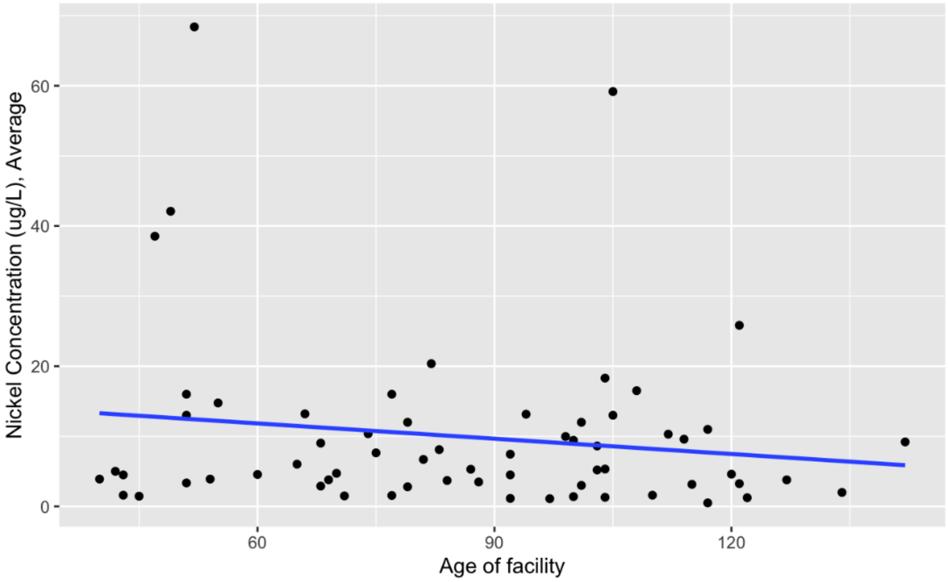
- **By age of facility**

The Load of Nickel changes by age of facility



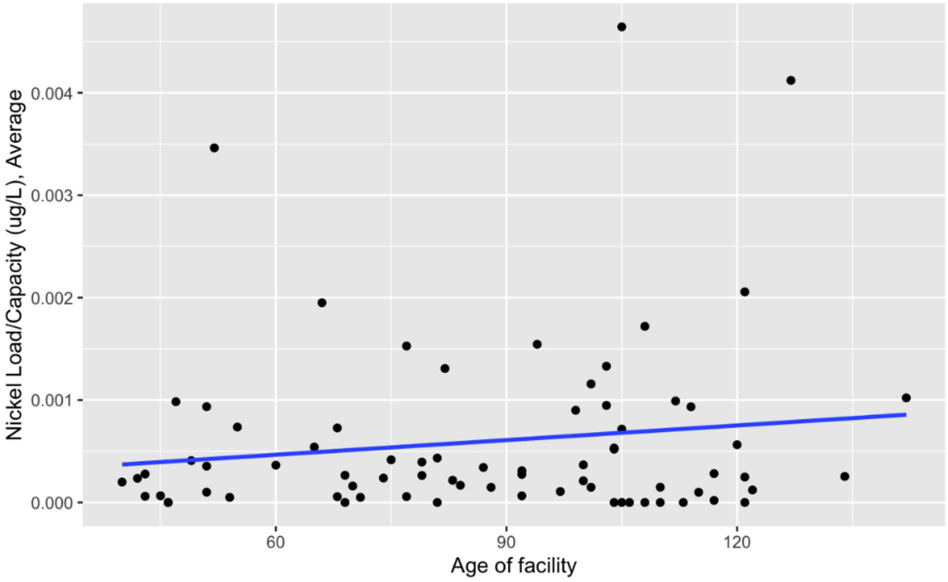
R^2 = 0.003, p-value = 0.274

The Concentration of Nickel changes by age of facility



R^2 = 0.0073, p-value = 0.231

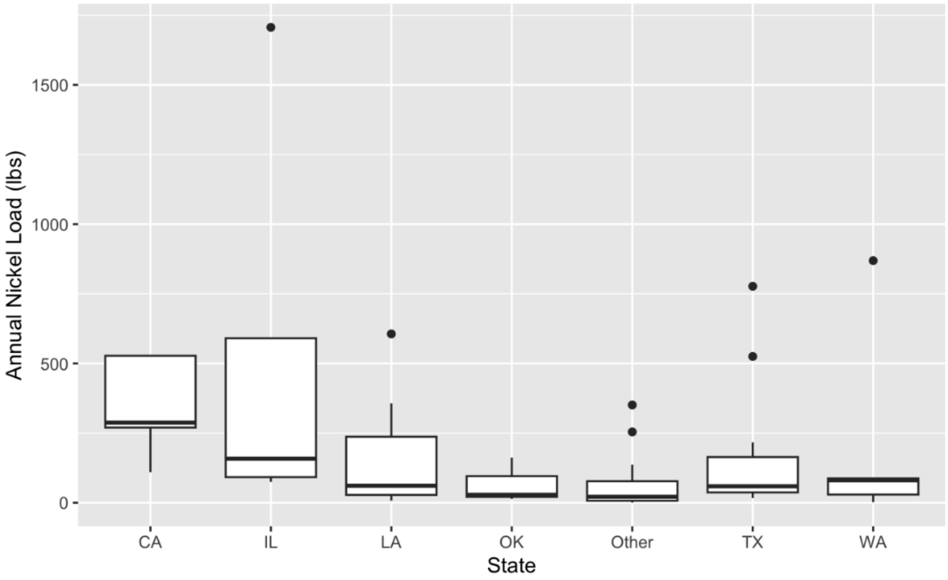
The Load / Capacity of Nickel changes by age of facility



R^2 = 0.0068, p-value = 0.225

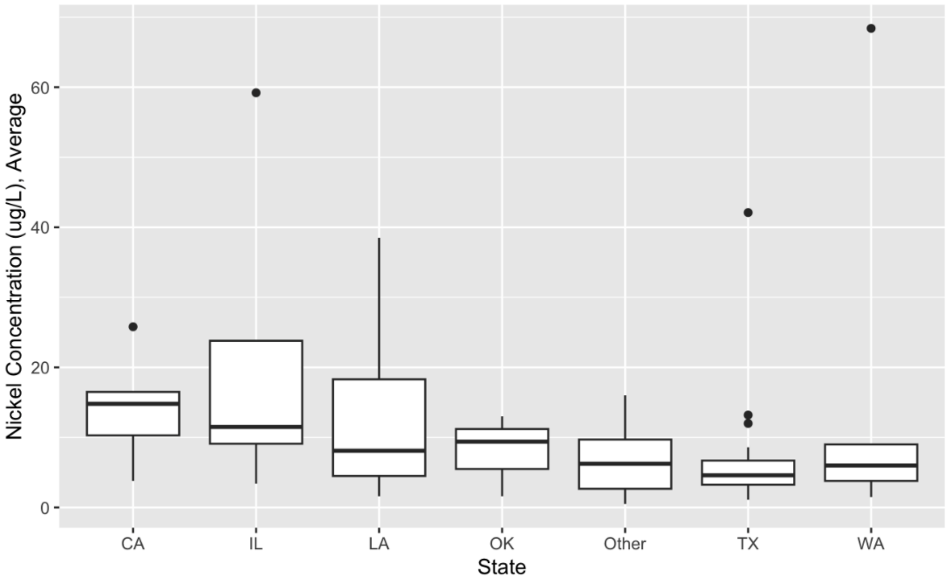
- **By state**

The Load of Nickel changes by state



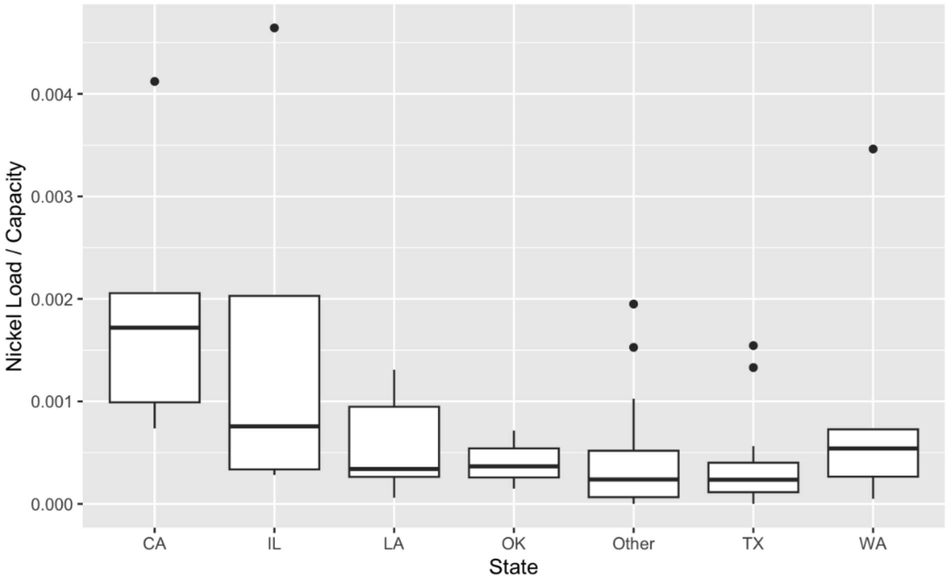
F-value = 2.6695, p-value = 0.02311

The Concentration of Nickel changes by state



F-value = 2.6695, p-value = 0.02311

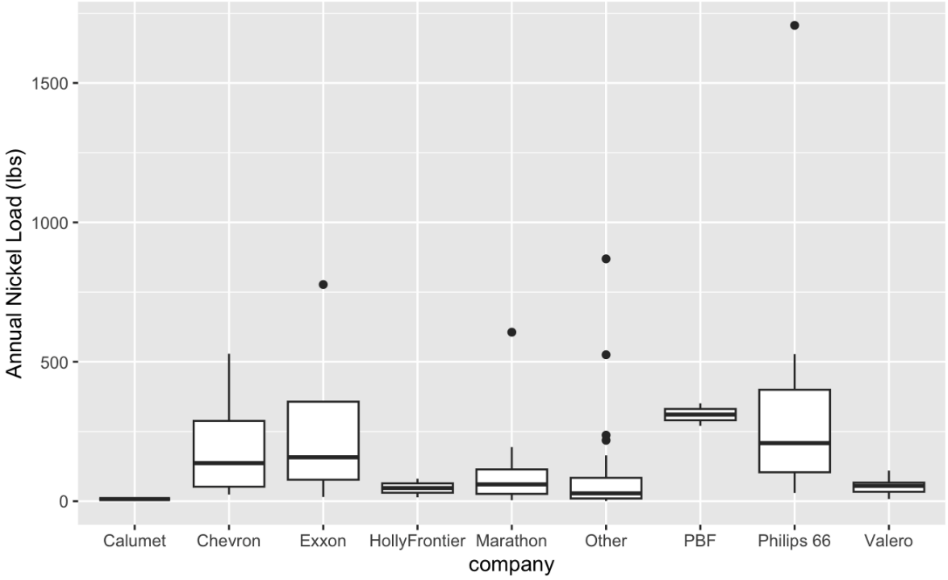
The Load / Capacity of Nickel changes by state



F-value = 3.204, p-value = 0.0075

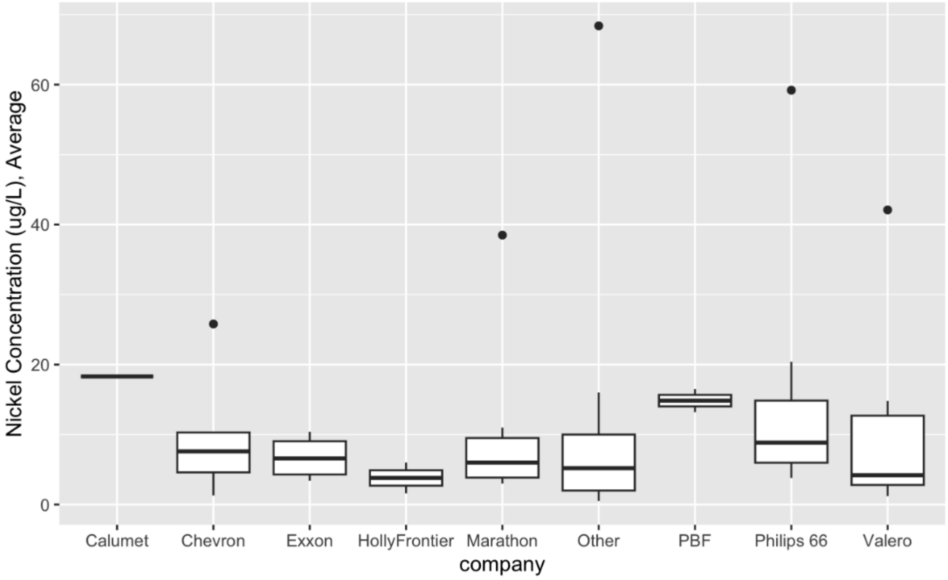
- **By company**

The Load of Nickel changes by company



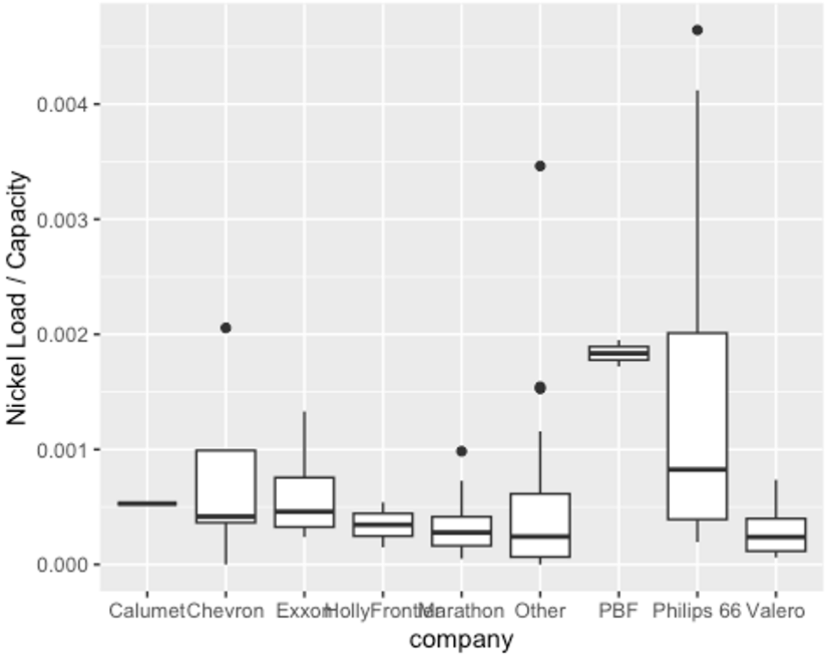
F-value = 3.352, p-value = 0.174

The Concentration of Nickel changes by company



F-value = 0.435, P-value = 0.8952

The Load / Capacity of Nickel changes by company

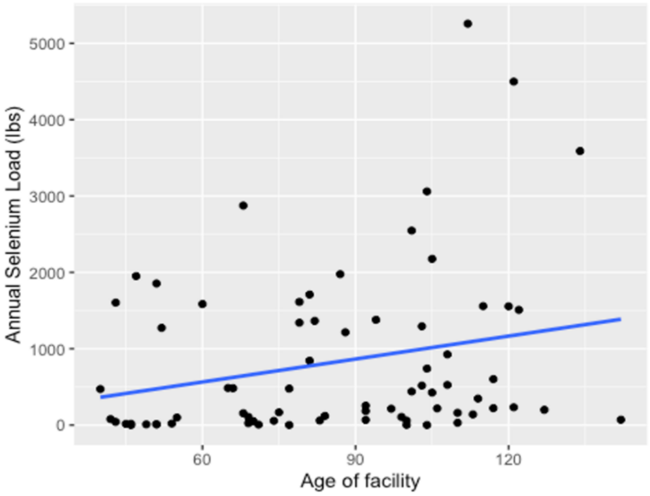


F-value = 2.28, P-value = 0.033

iii. Selenium

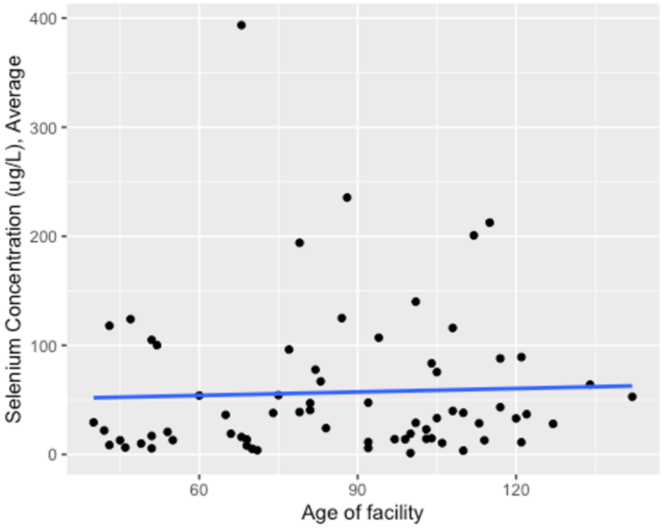
- **By age of facility**

The Load of Selenium changes by age of facility



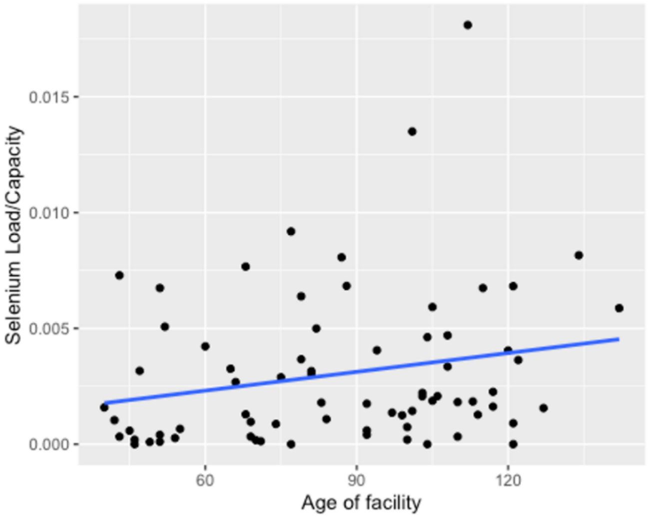
R^2 = 0.003, p-value =0.274

The Concentration of Selenium changes by age of facility



R^2 = -0.013, p-value =0.7344

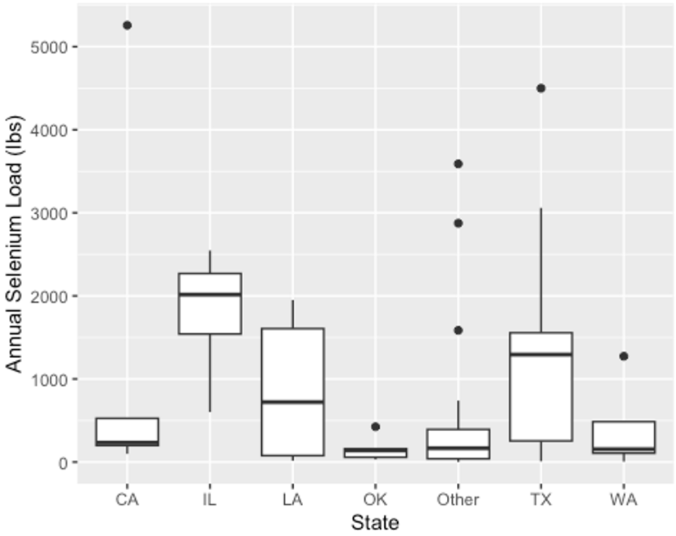
The Load / Capacity of Selenium changes by age of facility



R^2 = 0.034, p-value =0.066

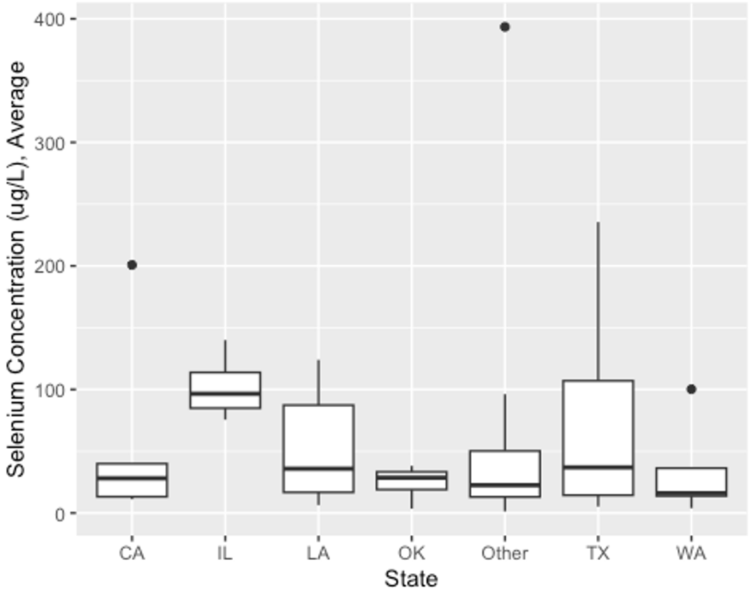
- **By state**

The Load of Selenium changes by state



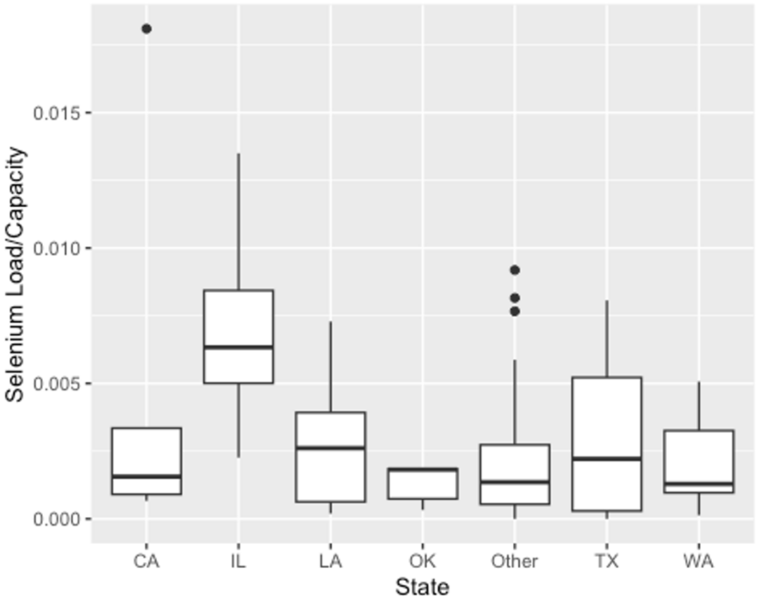
F-value = 2.294, P-value = 0.044

The Concentration of Selenium changes by state



F-value = 1.007, P-value = 0.428

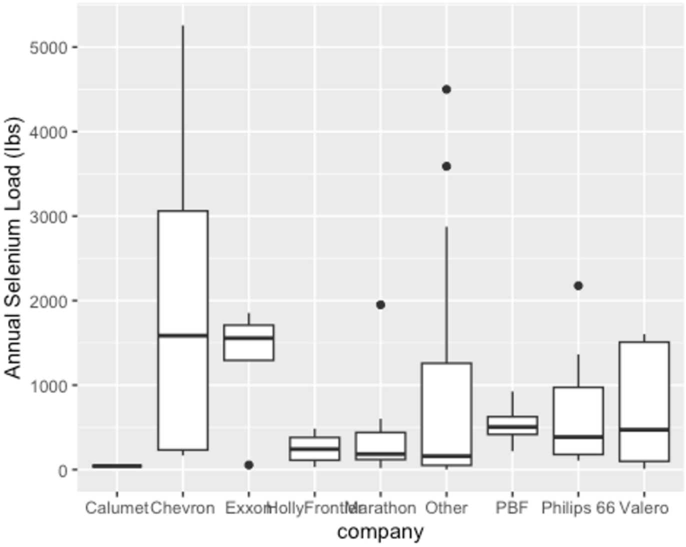
The Load / Capacity of Selenium changes by state



F-value = 2.038, P-value = 0.072

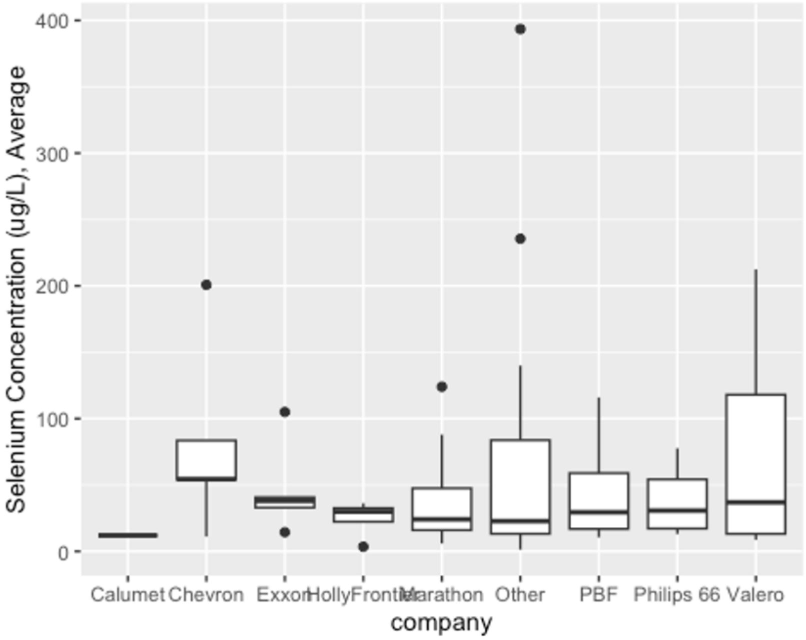
- **By Company**

The Load of Selenium changes by company



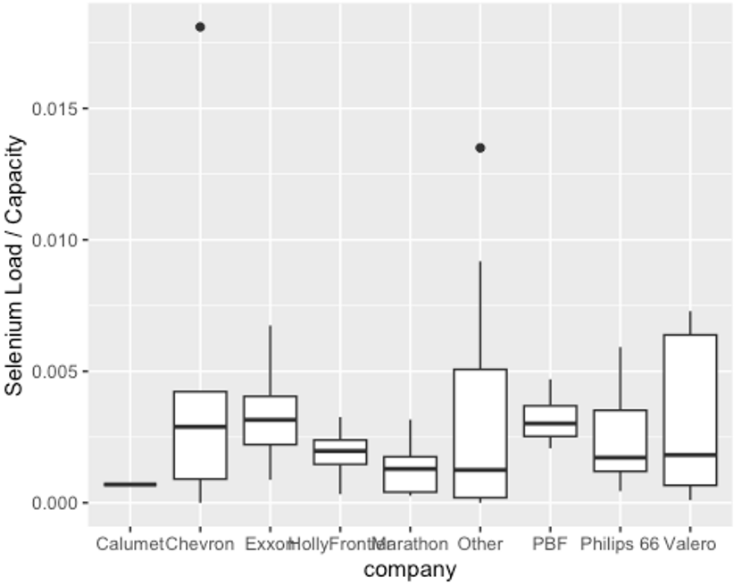
F-value = 1.43, P-value = 0.206

The Concentration of Selenium changes by age of company



F-value = 0.4275, P-value = 0.6729

The Load / Capacity of Selenium changes by company



F-value = 0.7203, P-value = 0.6729

Appendix C – Most and Least Polluting Companies by Target Pollutant

To understand if the most and least

i. Nickel

- **By Load**

Top 10 Most Polluting by Load

Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Annual Nickel Load (lbs)
Phillips 66 Wood River Refinery	Wood River	IL	367,500	1,706.6
BP Cherry Point Refinery	Ferndale	WA	251,000	869.1
ExxonMobil Baytown Refinery	Baytown	TX	584,000	777.0
Marathon Garyville Refinery	Garyville	LA	616,000	606.0
Chevron Richmond Refinery	Richmond	CA	257,200	528.8
Phillips 66 Rodeo Refinery	Rodeo	CA	128,000	527.5
Pemex Deer Park Refinery	Deer Park	TX	340,000	525.1
Phillips 66 Lake Charles Refinery	Westlake	LA	273,000	357.0
PBF Delaware City Refinery	Delaware City	DE	180,000	351.0
Chevron El Segundo Refinery	El Segundo	CA	290,500	287.8

Top 10 Least Polluting by Load

Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Annual Nickel Load (lbs)
Valero Meraux Refinery	Meraux	LA	128,000	7.8
Calumet Cotton Valley Refinery	Cotton Valley	LA	14,000	7.4
Suncor Energy Commerce City Refinery	Commerce City West	CO	111700	7.3
CountryMark Mount Vernon Refinery	Mount Vernon	IN	33,400	7.2
Marathon Tesoro Kenai Refinery	Kenai	AK	72,000	3.6
CVR Coffeyville Refinery	Coffeyville	KS	136,000	2.8
Par Pacific Tacoma Refinery	Tacoma	WA	42,000	2.1
Ergon Vicksburg Refinery	Vicksburg	MS	27,300	1.8
Cross Oil Smackover Refinery	Smackover	AR	7,700	1.6
Hunt Southland Refinery	Sandersville	MS	12,500	0.7

- **By Concentration**

Top 10 Least Polluting by Concentration				
Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Nickel Concentration (ug/L), Average
Calcasieu Refining Lake Charles Refinery	Lake Charles	LA	137,000	Below Detection Level
PBF Chalmette Refinery	Chalmette	LA	197,000	Below Detection Level
PBF Paulsboro Refinery	Paulsboro	NJ	105,000	Below Detection Level
HollyFrontier Tulsa East Refinery	Tulsa East	OK	75,500	Below Detection Level
ExxonMobil Baton Rouge Refinery	Baton Rouge	LA	542,000	Below Detection Level
Calumet Shreveport Refinery	Shreveport	LA	60,000	Below Detection Level
Vertex Refining Saraland Refinery	Saraland	AL	90,600	Below Detection Level
Valero Ardmore Refinery	Ardmore	OK	88,000	Below Detection Level
Marathon Mandan Refinery	Mandan	ND	74,000	Below Detection Level
Delek Krotz Springs Refinery	Krotz Springs	LA	83,000	Below Detection Level

Top 10 Most Polluting by Concentration				
Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Nickel Concentration (ug/L), Average
BP Cherry Point Refinery	Ferndale	WA	251,000	68.4
Phillips 66 Wood River Refinery	Wood River	IL	367,500	59.2
Valero Three Rivers Refinery	Three Rivers	TX	91,000	42.1
Marathon Garyville Refinery	Garyville	LA	616,000	38.5
Chevron Richmond Refinery	Richmond	CA	257,200	25.8
Phillips 66 Lake Charles Refinery	Westlake	LA	273,000	20.4
Calumet Cotton Valley Refinery	Cotton Valley	LA	14,000	18.3
PBF Martinez Refinery	Martinez	CA	157,000	16.5
Hunt Refining Tuscaloosa Refinery	Tuscaloosa	AL	52,000	16.0
Par Hawaii Refinery	Ewa Beach	HI	95,000	16.0

- **By Load/Capacity**

Top 10 Least Polluting by Load/Capacity					
Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Annual Nickel Load (lbs)	Annual Nickel Load (lbs)/Capacity
Calcasieu Refining Lake Charles Refinery	Lake Charles	LA	137,000	-	0.00
PBF Chalmette Refinery	Chalmette	LA	197,000	-	0.00
PBF Paulsboro Refinery	Paulsboro	NJ	105,000	-	0.00
HollyFrontier Tulsa East Refinery	Tulsa East	OK	75,500	-	0.00
ExxonMobil Baton Rouge Refinery	Baton Rouge	LA	542,000	-	0.00
Calumet Shreveport Refinery	Shreveport	LA	60,000	-	0.00
Vertex Refining Saraland Refinery	Saraland	AL	90,600	-	0.00
Valero Ardmore Refinery	Ardmore	OK	88,000	-	0.00
Marathon Mandan Refinery	Mandan	ND	74,000	-	0.00
Delek Krotz Springs Refinery	Krotz Springs	LA	83,000	-	0.00

Top 10 Most Polluting by Load/Capacity					
Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Annual Nickel Load (lbs)	Annual Nickel Load (lbs)/Capacity
Phillips 66 Wood River Refinery	Wood River	IL	367,500	1,706.6	4.68
BP Cherry Point Refinery	Ferndale	WA	251,000	869.1	2.38
ExxonMobil Baytown Refinery	Baytown	TX	584,000	777.0	2.13
Marathon Garyville Refinery	Garyville	LA	616,000	606.0	1.66
Chevron Richmond Refinery	Richmond	CA	257,200	528.8	1.45
Phillips 66 Rodeo Refinery	Rodeo	CA	128,000	527.5	1.45
Pemex Deer Park Refinery	Deer Park	TX	340,000	525.1	1.44
Phillips 66 Lake Charles Refinery	Westlake	LA	273,000	357.0	0.98
PBF Delaware City Refinery	Delaware City	DE	180,000	351.0	0.96
Chevron El Segundo Refinery	El Segundo	CA	290,500	287.8	0.79

ii. Selenium

- **By Load**

Top 10 Most Polluting by Load				
Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Annual Selenium Load (lbs)
Chevron El Segundo Refinery	El Segundo	CA	290,500	5,257.2
Motiva Port Arthur Refinery	Port Arthur	TX	659,700	4,499.4
BP Whiting Refinery	Whiting	IN	440,000	3,589.1
Chevron Pasadena Refinery, LyondellBasell Houston Refinery, and Kinder Morgan Galena Park Refinery (via Washburn Tunnel Facility)	Pasadena	TX		3,060.0
Flint Hills Resources Pine Bend Refinery	Saint Paul	MN	375,000	2,874.8
Citgo Lemont Refinery	Lemont	IL	188,700	2,547.6
Phillips 66 Wood River Refinery	Wood River	IL	367,500	2,176.4
TotalEnergies Port Arthur Refinery	Port Arthur	TX	245,000	1,976.8
Marathon Garyville Refinery	Garyville	LA	616,000	1,950.6
Exxonmobil Joliet Refinery	Joliet	IL	275,000	1,854.5

Top 10 Least Polluting by Load				
Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Annual Selenium Load (lbs)
Marathon Mandan Refinery	Mandan	ND	74,000	24.2
Marathon Tesoro Kenai Refinery	Kenai	AK	72,000	19.1
Delek Krotz Springs Refinery	Krotz Springs	LA	83,000	16.2
Ergon Vicksburg Refinery	Vicksburg	MS	27,300	15.9
Par Hawaii Refinery	Ewa Beach	HI	95,000	10.2
Ergon Newell Refinery	Newell	WV	23,000	9.3
Valero Three Rivers Refinery	Three Rivers	TX	91,000	8.8
Par Pacific Tacoma Refinery	Tacoma	WA	42,000	5.5
Vertex Refining Saraland Refinery	Saraland	AL	90,600	3.5
Cross Oil Smackover Refinery	Smackover	AR	7,700	1.5

- **By Concentration**

Top 10 Most Polluting by Concentration				
Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Selenium Concentration (ug/L), Average
Flint Hills Resources Pine Bend Refinery	Saint Paul	MN	375,000	393.5
Citgo Corpus Christi Refinery	Corpus Christi	TX	177,839	235.5
Valero Texas City Refinery	Texas City	TX	231,000	212.5
Chevron El Segundo Refinery	El Segundo	CA	290,500	200.8
Valero Houston Refinery	Houston	TX	210,000	194.0
Citgo Lemont Refinery	Lemont	IL	188,700	140.0
TotalEnergies Port Arthur Refinery	Port Arthur	TX	245,000	125.0
Marathon Garyville Refinery	Garyville	LA	616,000	124.0
Valero St. Charles Norco Refinery	Norco	LA	220,000	118.0
PBF Chalmette Refinery	Chalmette	LA	197,000	116.0

Top 10 Least Polluting by Concentration				
Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Selenium Concentration (ug/L), Average
Valero Three Rivers Refinery	Three Rivers	TX	91,000	8.6
Valero Meraux Refinery	Meraux	LA	128,000	8.1
Marathon Mandan Refinery	Mandan	ND	74,000	6.4
Delek Krotz Springs Refinery	Krotz Springs	LA	83,000	5.9
Marathon Galveston Bay Refinery	Galveston Bay	TX	625,000	5.6
Vertex Refining Saraland Refinery	Saraland	AL	90,600	5.6
Ergon Newell Refinery	Newell	WV	23,000	5.2
Flint Hills Resources Corpus Christi West Refinery	Corpus Christi, West	TX	275,000	3.9
Par Pacific Tacoma Refinery	Tacoma	WA	42,000	3.5
HollyFrontier Tulsa West Refinery	Tulsa West	OK	91,020	1.3

- **By Load/Capacity**

Top 10 Most Polluting by Load/Capacity					
Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Annual Selenium Load (lbs)	Annual Selenium Load (lbs)/Capacity
Chevron El Segundo Refinery	El Segundo	CA	290,500	5,257.2	0.02
Citgo Lemont Refinery	Lemont	IL	188,700	2,547.6	0.01
Hunt Refining Tuscaloosa Refinery	Tuscaloosa	AL	52,000	477.7	0.01
BP Whiting Refinery	Whiting	IN	440,000	3,589.1	0.01
TotalEnergies Port Arthur Refinery	Port Arthur	TX	245,000	1,976.8	0.01
Flint Hills Resources Pine Bend Refinery	Saint Paul	MN	375,000	2,874.8	0.01
Valero St. Charles Norco Refinery	Norco	LA	220,000	1,603.4	0.01
Citgo Corpus Christi Refinery	Corpus Christi	TX	177,839	1,215.1	0.01
Motiva Port Arthur Refinery	Port Arthur	TX	659,700	4,499.4	0.01
Exxonmobil Joliet Refinery	Joliet	IL	275,000	1,854.5	0.01

Top 10 Least Polluting by Load/Capacity					
Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Annual Selenium Load (lbs)	Annual Selenium Load (lbs)/Capacity
Valero Meraux Refinery	Meraux	LA	128,000	41.8	0.00
HollyFrontier Tulsa West Refinery	Tulsa West	OK	91,020	29.7	0.00
Marathon Tesoro Kenai Refinery	Kenai	AK	72,000	19.1	0.00
Delek Krotz Springs Refinery	Krotz Springs	LA	83,000	16.2	0.00
Cross Oil Smackover Refinery	Smackover	AR	7,700	1.5	0.00
Flint Hills Resources Corpus Christi West Refinery	Corpus Christi, West	TX	275,000	48.8	0.00
Par Pacific Tacoma Refinery	Tacoma	WA	42,000	5.5	0.00
Par Hawaii Refinery	Ewa Beach	HI	95,000	10.2	0.00
Valero Three Rivers Refinery	Three Rivers	TX	91,000	8.8	0.00
Vertex Refining Saraland Refinery	Saraland	AL	90,600	3.5	0.00

iii. Ammonia

- **By Load**

Top 10 Most Polluting by Load

Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Annual Ammonia-N Load (lbs)
Phillips 66 Alliance Belle Chasse Refinery	Belle Chasse	LA	269,140	255,032
Valero St. Charles Norco Refinery	Norco	LA	220,000	199,166
ExxonMobil Baytown Refinery	Baytown	TX	584,000	116,412
Marathon Galveston Bay Refinery	Galveston Bay	TX	625,000	74,244
Phillips 66 Lake Charles Refinery	Westlake	LA	273,000	61,228
Valero Corpus Christi Bill Greehey Refinery	Corpus Christi	TX	297,000	59,867
Citgo Lake Charles Refinery	Lake Charles	LA	440,000	56,848
PBF Chalmette Refinery	Chalmette	LA	197,000	53,953
Motiva Port Arthur Refinery	Port Arthur	TX	659,700	51,865
Phillips 66 Sweeny Refinery	Sweeny	TX	278,900	43,371

Top 10 Least Polluting by Load

Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Annual Ammonia-N Load (lbs)
Calumet Cotton Valley Refinery	Cotton Valley	LA	14,000	51
Par Pacific Tacoma Refinery	Tacoma	WA	42,000	150
Par Hawaii Refinery	Ewa Beach	HI	95,000	180
Calcasieu Refining Lake Charles Refinery	Lake Charles	LA	137,000	248
Hunt Southland Refinery	Sandersville	MS	12,500	336
Marathon Canton Refinery	Canton	OH	105,000	385
Vertex Refining Saraland Refinery	Saraland	AL	90,600	462
Phillips 66 Ferndale Refinery	Ferndale	WA	110,500	610
Marathon Robinson Refinery	Robinson	IL	266,000	695
Cross Oil Smackover Refinery	Smackover	AR	7,700	735

- **By Concentration**

Top 10 Most Polluting by Concentration				
Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Ammonia-N Concentration (mg/L), Average
Phillips 66 Alliance Belle Chasse Refinery	Belle Chasse	LA	269,140	69.55
Ergon Newell Refinery	Newell	WV	23,000	36.65
Ergon Vicksburg Refinery	Vicksburg	MS	27,300	23.14
Valero St. Charles Norco Refinery	Norco	LA	220,000	14.18
Marathon Tesoro Kenai Refinery	Kenai	AK	72,000	9.05
United Refining Warren Refinery	Warren	PA	70,000	8.50
Placid Refining Port Allen Refinery	Port Allen	LA	82,500	7.34
Delek Krotz Springs Refinery	Krotz Springs	LA	83,000	5.52
Valero Corpus Christi Bill Greehey Refinery	Corpus Christi	TX	297,000	5.41
Chevron Salt Lake City Refinery	Salt Lake City	UT	57,600	4.44

Top 10 Least Polluting by Concentration				
Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Ammonia-N Concentration (mg/L), Average
Citgo Lemont Refinery	Lemont	IL	188,700	0.05
Chevron Pasadena Refinery, LyondellBasell Houston Refinery, and Kinder Morgan Galena Park Refinery (via Washburn Tunnel Facility)	Pasadena	TX	-	0.06
Phillips 66 Ferndale Refinery	Ferndale	WA	110,500	0.07
Marathon Robinson Refinery	Robinson	IL	266,000	0.10
Par Pacific Tacoma Refinery	Tacoma	WA	42,000	0.10
Valero Meraux Refinery	Meraux	LA	128,000	0.11
Exxonmobil Beaumont Refinery	Beaumont	TX	384,400	0.11
Marathon Canton Refinery	Canton	OH	105,000	0.13
Calumet Cotton Valley Refinery	Cotton Valley	LA	14,000	0.14
Calcasieu Refining Lake Charles Refinery	Lake Charles	LA	137,000	0.15

- **By Load/Capacity**

Top 10 Most Polluting by Load/Capacity

Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Annual Ammonia-N Load (lbs)	Annual Ammonia-N Load (lbs)/Operational Capacity
Ergon Vicksburg Refinery	Vicksburg	MS	27,300	27,924	1.022865201
Phillips 66 Alliance Belle Chasse Refinery	Belle Chasse	LA	269,140	255,032	0.947581185
Valero St. Charles Norco Refinery	Norco	LA	220,000	199,166	0.905299545
Ergon Newell Refinery	Newell	WV	23,000	13,378	0.581652174
American Refining Bradford Refinery	Bradford	PA	11,800	4,206	0.356440678
United Refining Warren Refinery	Warren	PA	70,000	20,754	0.296485714
PBF Chalmette Refinery	Chalmette	LA	197,000	53,953	0.273871937
Delek Krotz Springs Refinery	Krotz Springs	LA	83,000	21,591	0.260129036
Placid Refining Port Allen Refinery	Port Allen	LA	82,500	20,043	0.242941333
Chevron Salt Lake City Refinery	Salt Lake City	UT	57,600	13,835	0.240190972

Top 10 Least Polluting by Load/Capacity

Refinery	City	State	Operable Capacity, 2021 (bbls/stream day)	Annual Ammonia-N Load (lbs)	Annual Ammonia-N Load (lbs)/Operational Capacity
Calcasieu Refining Lake Charles Refinery	Lake Charles	LA	137,000	248	0.001811124
Par Hawaii Refinery	Ewa Beach	HI	95,000	180	0.001894737
Marathon Robinson Refinery	Robinson	IL	266,000	695	0.002613158
Par Pacific Tacoma Refinery	Tacoma	WA	42,000	150	0.003564762
Calumet Cotton Valley Refinery	Cotton Valley	LA	14,000	51	0.003642857
Marathon Canton Refinery	Canton	OH	105,000	385	0.0036666
ExxonMobil Baton Rouge Refinery	Baton Rouge	LA	542,000	2,693	0.00496893
Vertex Refining Saraland Refinery	Saraland	AL	90,600	462	0.005096689
Phillips 66 Ferndale Refinery	Ferndale	WA	110,500	610	0.005524299
Phillips 66 Bayway Refinery	Linden	NJ	272,100	1,550	0.005696435

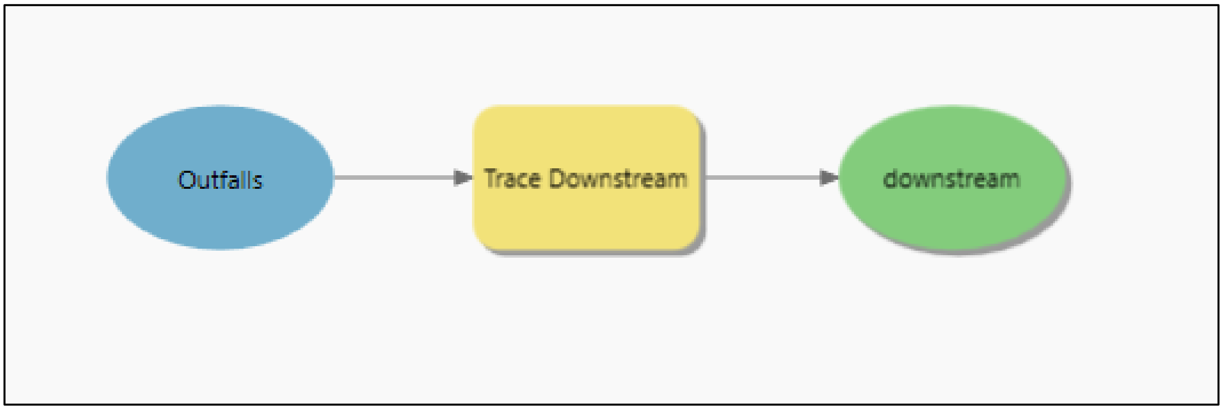
Appendix D – Downstream Attributes Database (GIS Analysis)

The final database contains the sociodemographic attributes and total number of drinking water surface intake facilities downstream from the refinery outfall locations affected by the lax in implementation of ELGs.

Appendix E – GIS Models

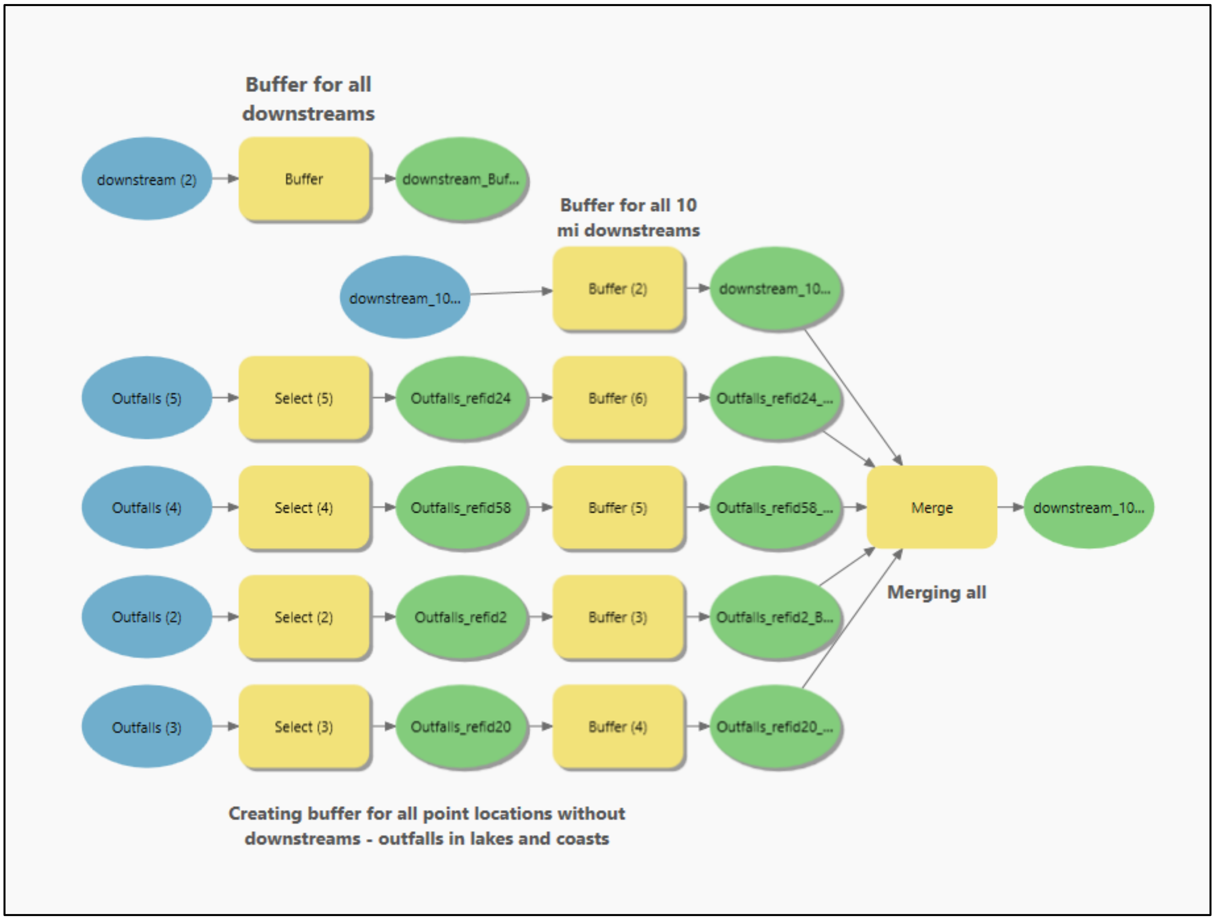
This appendix contains the workflow of the models used to analyze the downstream sociodemographic characteristics for each of the 77 outfalls and the number of drinking water intake facilities. The result of the analyses was a final database with the downstream attributes, found in Appendix B.

1. Tracing Downstream from the Outfalls

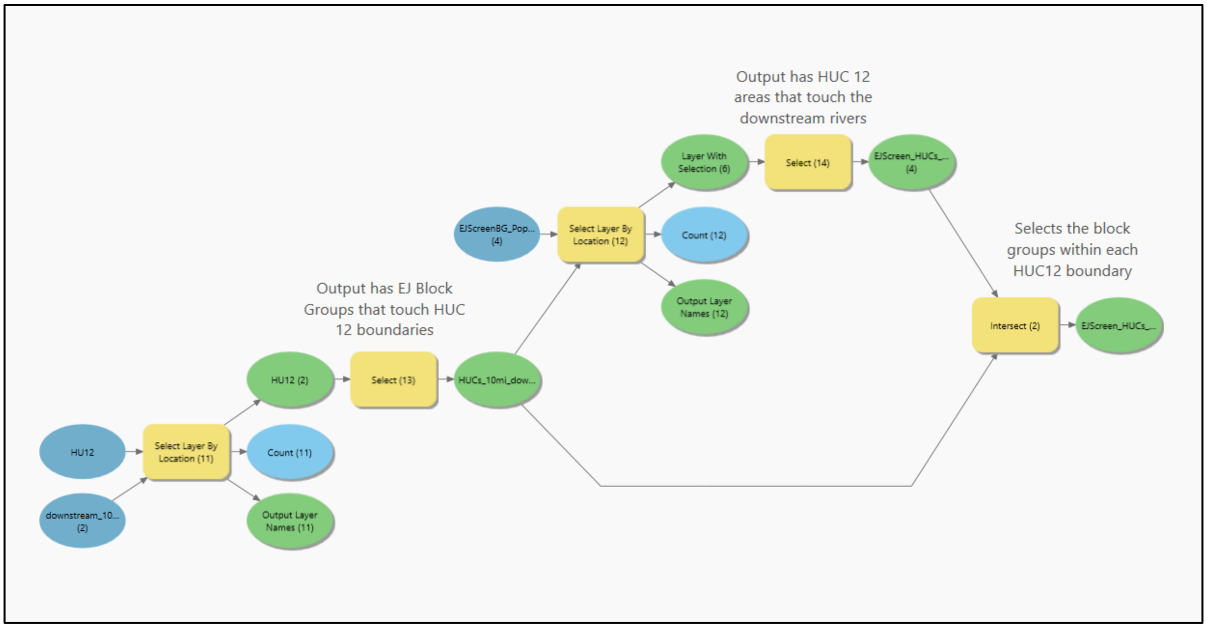


2. Determining the 10-mile downstream segments

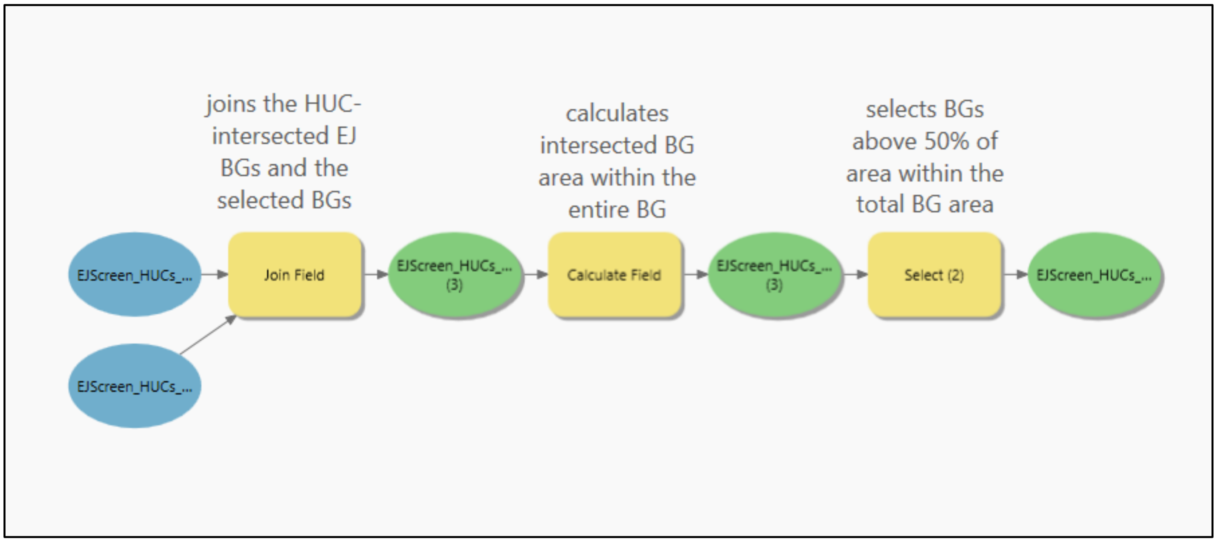
3. Creating 3-mile buffers from the downstreams



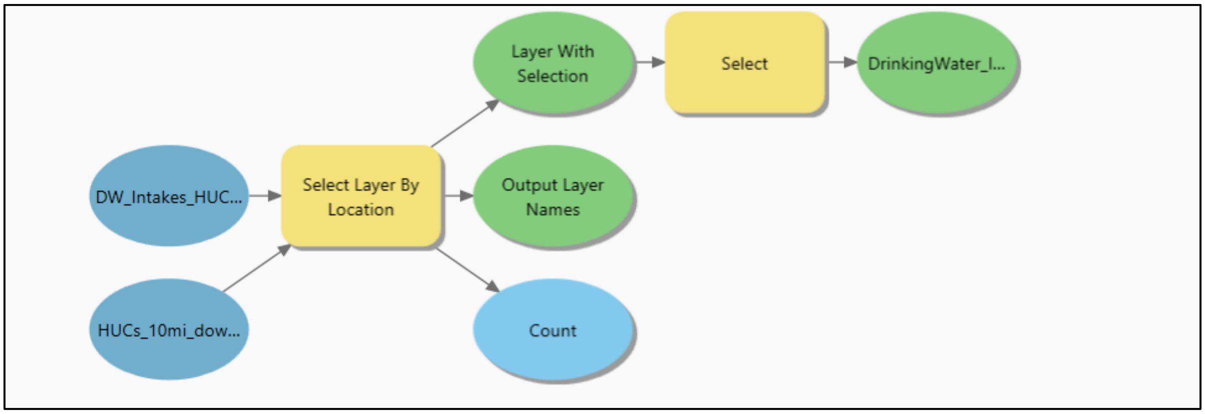
4. Selecting the census block groups (containing sociodemographic attributes) within the affected downstream HUC12 subwatersheds



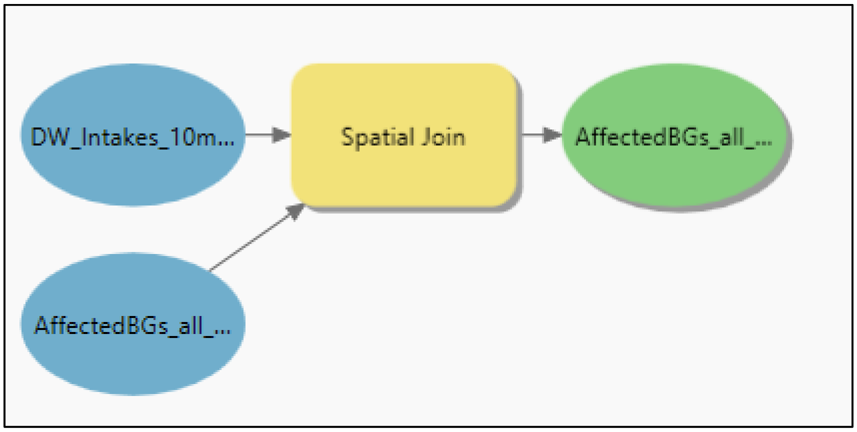
5. Selecting affected block groups that significantly fall within the HUC12 subwatersheds



6. Determining the number of drinking water intake facilities within the downstream HUC12 subwatersheds



7. Combining the sociodemographic attributes and drinking water intake facilities for downstreams



8. Calculating total percentage of people of colour, low-income, children under the age of 5, people over the age of 65, unemployed, limited english-speaking population, and population with less than highschool education for each downstream from the outfalls