



Assessing the quantity and toxicity of chemical releases from TRI facilities in Upstate New York

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Abstract

Pollutant chemical releases and their toxicological profiles have been investigated by many researchers in the past; however, little work of this kind has been conducted in the Upstate New York area. The objectives of this study were to compare the pollutant releases from Toxic Release Inventory (TRI) facilities in Upstate New York, both by quantity and toxicity. Using hierarchical clustering, seven unique residential clusters were created from nine population demographics representing neighborhood-based socioeconomic status. TRI facilities were geocoded into the residential clusters, and the quantity and toxicity of chemicals released from these facilities were obtained. The facilities in the Minority Working Class and Working Class clusters released the greatest quantity of chemicals. However, when looking at the toxicity of the chemicals released, reporting only the quantity of polluting chemicals had the potential to underestimate the potential toxicological risk faced by the communities surrounding these facilities; this was true for both the overall quantity of chemicals released and when looking at carcinogens released, in particular. Lastly, it was seen that not including toxicity in reported results might hide many toxic chemicals that are released in low quantities. The use of chemical weighing systems in studies such as this is imperative to fully inform individuals of the toxic chemicals being released within their communities.

Keywords Toxic Release Inventory (TRI) Facilities · Chemical release quantity · Chemical toxicity · Risk Screening Environmental Indicators (RSEI) Model

Introduction

In 1986, the Emergency Planning and Community Right-to-Know Act (EPCRA) was passed by Congress with the goal of protecting and preparing communities for chemical accidents, should they occur. Within EPCRA, there are

four major sections: Sect. 302 to 303 (emergency planning), Sect. 304 (emergency release notification), Sects. 311 and 312 (hazardous chemical inventory reporting), and Sect. 313 (Toxics Release Inventory) (United States Environmental Protection Agency 2020a). The Toxics Release Inventory (TRI) program tracks the management of over 650 chemicals across the USA that may pose a threat to human health or the environment; the facilities that release these chemicals are known as TRI facilities. TRI facilities are required to report the annual quantity of each chemical released to the environment as well as (if applicable) the quantity of each chemical managed through recycling and other waste reduction techniques (United States Environmental Protection Agency 2020b).

Researchers in the environmental justice field have been using TRI facility data, coupled with neighborhood socioeconomic status (SES) and demographic data, to look for associations between the locations of polluting facilities and the SES of the neighborhoods surrounding them. Prior work has found that TRI facilities and other hazardous waste sites tend to be located in areas with high concentrations of minorities

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and low-income individuals (United Church of Christ. Commission for Racial Justice 1987; Mohai et al. 2009; Flores et al. 2020). However, other researchers have found that in addition to race and income, other variables such as the type of housing and percentage of homeownership (Pastor et al. 2005; Sicotte 2010), education level (Sicotte 2010), and unemployment level (Bouwes et al. 2001) are also correlated with patterns of disproportionate risk, suggesting that various metrics of SES may be influential when studying environmental inequality.

Previously, we conducted a study in Upstate New York where the greatest number of facilities and the highest quantities of releases from these facilities were located in areas with a large percentage of residents working in non-managerial positions (Charette et al. 2021). However, in that study, the toxicity of the chemical releases for these facilities was not addressed. Since the toxicity of chemicals widely vary, assessing only the quantity of chemicals a facility is releasing could potentially underestimate the risk to the people living in adjacent neighborhoods (Lim et al. 2010; Taylor et al. 2020; Luo and Li 2021). For example, Lim et al. (2010) completed a quantity- and toxicity-based study of chemicals released from TRI facilities. This group utilized toxicity potentials that were derived from the Environmental Protection Agency's (EPA) Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI). This tool provides characterization factors that quantify potential impacts that releases have on specific impact categories, including human health impacts and ecotoxicity (United States Environmental Protection Agency 2021a). Ultimately, none of the most toxic chemicals identified through the toxicity-based evaluation would have been identified by quantity-based evaluation (Lim et al. 2010). This finding was due to the discrepancies in chemical releases between hazardous and non-hazardous chemicals; it is possible that more toxic chemicals can be released in smaller amounts but get overshadowed by the ubiquitous releases of less toxic chemicals in the same environment.

Thus, taking the work of Lim et al. (2010) into account, we expanded upon our prior research by examining how different demographic groups in Upstate New York are exposed to varying levels of toxic chemicals using the EPA's Risk-Screening Environmental Indicators (RSEI) data. The first objective of this study was to compare the pollutant releases from TRI facilities in Upstate New York by quantity and toxicity to determine whether differences were present between the two different outcomes; this information will allow us to determine whether using the quantity of chemical releases is valid as a metric for potential harm to human health in the geographical area being studied. In our second study objective, we examined whether carcinogenic chemical releases were elevated in certain residential communities. We focused on carcinogenic releases because, in the USA,

cancer is the second leading cause of death; more than 1.6 million residents are diagnosed with cancer, and approximately 600,000 residents pass away from cancer, each year (Centers for Disease Control and Prevention 2020). Therefore, through this analysis, we can further refine our dataset to look at specific chemical compounds known for their suspected or known ties to major and devastating diseases. Based on the results from these two study objectives, we hope to increase our understanding about the effectiveness of risk-based chemical weighting schemes, rather than quantity-only metrics, specifically regarding the suitability of the metric when communicating health-based and exposure risks in vulnerable communities.

Methods

Study location

Similar to past work (Charette et al. 2021), four counties in Upstate New York (Erie, Monroe, Onondaga, and Albany) were used in this study. Each county contained a major Upstate New York city, with Buffalo in Erie County, Rochester in Monroe County, Syracuse in Onondaga County, and Albany, the state capital of New York, in Albany County. We chose this study area because the cities of Buffalo, Rochester, Syracuse, and Albany all have large concentrations of communities within them that have been identified by the New York Department of Environmental Conservation (NY DEC) as potential environmental justice areas (New York State Department of Environmental Conservation 2021a). According to the NY DEC, these potential environmental justice areas represent United States Census block groups of 250 to 500 households that had populations which met or exceeded at least one of the following statistical thresholds: (1) at least 52.42% of the population in an urban area reporting themselves to be members of minority groups, (2) at least 26.28% of the population in a rural area reporting themselves to be members of minority groups, and/or (3) at least 22.82% of the population in an urban or rural area that had household incomes below the federal poverty level (New York State Department of Environmental Conservation 2021b). Despite this information, little work has been done regarding environmental injustice in this location, prompting further investigation. Furthermore, the four counties examined are comparable in geographic location, land size, and presence of a major Upstate city. More data on county and city size can be found in Online Resource 1. The populations of these four counties differ, ranging from 295,000 people in Albany County to 941,000 people in Erie County; however, each major city houses approximately 30% of each county's total population (United States Census Bureau 2019). The four counties, Erie, Monroe, Onondaga, and Albany, were

comprised of 913, 601, 409, and 233 block groups, respectively, totaling 2156 block groups in total. However, 33 block groups, containing no population data, were excluded from the analyses, leaving 2123 block groups to be analyzed for this work.

Definition of residential clusters

When designing studies assessing neighborhood-associated socioeconomic status, there is no standard methodology stating which socioeconomic variables should be used (Messer et al. 2006). However, there are several categories of SES-associated variables that are influential in describing a neighborhood and have been highly utilized in past work (Messer et al. 2006; Mirowsky et al. 2017; Weaver et al. 2019); these categories include education, wealth, income, race/ethnicity, employment, housing, and land use. Thus, using these seven categories, nine specific SES-associated variables were identified (Fig. 1). A more detailed description and definition of these variables can be found in Charette et al. (2021) and in Fig. 1.

The most recent decennial Censuses do not include many of the variables required for this study, including the percentages of the population with at least a high school diploma, unemployed, working in non-managerial positions, and living below the poverty line; this limitation was noted previously (Charette et al. 2021). Therefore, the demographic data for this study was obtained from the 2000 decennial US Census, which is the most recent year this information could be obtained.

Ward’s hierarchical clustering method was used to aggregate the nine Census variables into neighborhood clusters based on similarities between the 2,123 block groups identified in the study area. Ward’s method is a bottom-up approach used to identify similarities within a group of

observations (Ward 1963; Mirowsky et al. 2017; Charette et al. 2021). To determine the optimal number of clusters for this analysis, the Friedman method was used (Friedman and Rubin 1967). As this study spanned four separate counties, the block groups within the clusters were not required to be adjacent to one another. More details on the seven clusters can be seen in Charette et al. (2021) and in Online Resource 2.

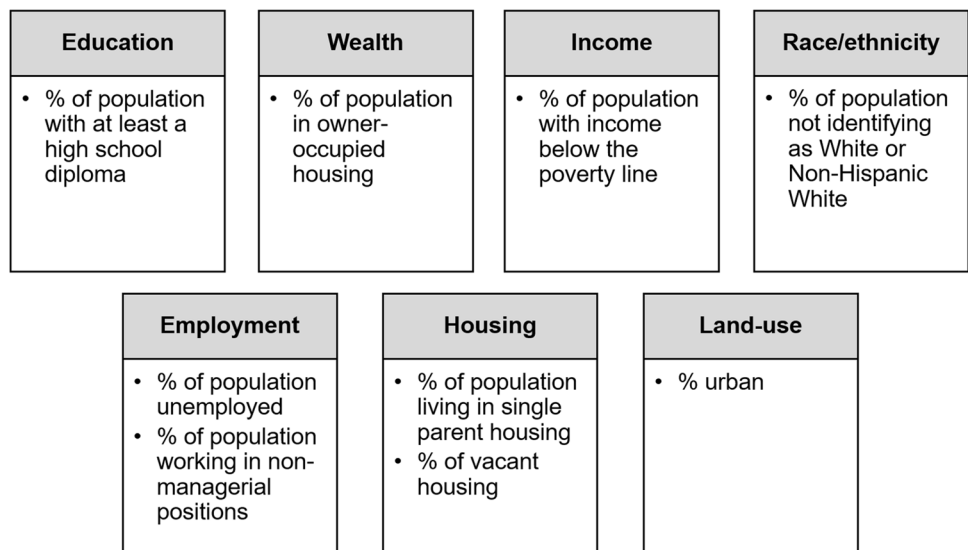
Toxic Release Inventory (TRI) facilities

To be consistent with 2000 Census data, the location and emissions data from all TRI facilities in the counties studied ($n = 189$ facilities) were collected from TRIExplorer from the year 2000. TRIExplorer is a tool managed by the EPA that can be used to obtain information about a TRI facility’s location, chemical releases, and treatment options (United States Environmental Protection Agency 2021b). Five facilities were in block groups excluded due to a lack of population data, leaving 184 TRI facilities to be included in the analysis. The facilities were geocoded into the residential clusters, and the number of facilities per cluster and the quantity of chemical releases were determined.

Risk-Screening Environmental Indicators (RSEI) data and calculations

The Risk-Screening Environmental Indicators (RSEI) Model, developed by the EPA, generally allows researchers to compare different chemicals and facilities to one another because the toxicity weights utilized in the RSEI model describe each chemical’s toxicity relative to other chemicals reported to the TRI program (United States Environmental Protection Agency 2021c). For this work, the model was used to compare all facilities across the study area using

Fig. 1 US Census categories ($n=7$) and variables ($n=9$) used to form the neighborhood clusters



the chemical-specific toxicity weights and the quantity of chemicals released (in pounds) from each facility.

To obtain the chemical-specific toxicity weights, the RSEI model was first used to obtain RSEI Modeled Hazard Scores. RSEI Modeled Hazard Scores were calculated for each chemical a facility releases by multiplying the quantity of the chemical released (in pounds) by the chemical's toxicity weight. The RSEI Modeled Hazard Score for all the chemicals released by a facility were then added together to create a Facility Score, which allows researchers to compare potential risks between different facilities based on the toxicity of all the compounds they are releasing. For this study, the RSEI Modeled Hazard Facility Scores (which will herein be referred to as "Facility Scores") were obtained from only those facilities that had catalogued on-site releases. On-site releases include stack and fugitive air releases; water releases; class I, class II, RCRA C, and other landfills; land treatment and application; surface impoundment; and other disposals (United States Environmental Protection Agency 2020c). Of the 184 TRI facilities in our study area, 55 facilities did not have EPA-generated Facility Scores and were removed from the analysis (Horvath et al. 1995), leaving 129 TRI facilities to be used in this study.

Of those 129 TRI facilities, the top three facilities with the highest Facility Scores per cluster were chosen to have their chemical releases more closely examined. Closely examining the top three facilities was done because previous research has shown that a small number of facilities within industry sectors have the potential to release a majority of the toxic releases within a given industry (Collins et al. 2016, 2020). Furthermore, we looked more closely at the top three facilities in more detail because the cluster with the lowest quantity of TRI facilities—the Wealthy Educated cluster—contained only three facilities within its boundaries; this allowed us to be consistent in our examination between the different SES clusters created.

The mass percentage of chemicals released from the top three polluting facilities, as well as the Facility Score percentage of the top three polluting facilities, were calculated for each cluster. The mass percentage was calculated by dividing the sum of the quantity of chemical releases (in pounds) from the top three polluting facilities by the total quantity of chemical releases (in pounds) per cluster and multiplying by 100. The Facility Score percentage was calculated by dividing the sum of the Facility Scores from the top three polluting facilities by the total sum of Facility Scores for the cluster and multiplying by 100.

Carcinogens

RSEI toxicity weights are based on a chemical's toxicological potential to cause chronic human health effects; as the potential increases, so does the toxicity weight. In this study,

carcinogens were examined because this class of chemicals has the potential to greatly influence human health (United States Environmental Protection Agency 2019). The quantity of carcinogenic chemicals released per cluster from the top three polluting facilities within our study area was calculated by summing the total on-site releases (in pounds) of chemicals classified as carcinogenic based on the Occupational Safety and Health Administration (OSHA) carcinogen category (United States Environmental Protection Agency 2020d). As stated previously, closely examining the top three facilities was done because previous research has shown that a small number of facilities within industry sectors have the potential to release a majority of the toxic releases within a given industry. For each carcinogen released within our study area, Relative Cancer Scores were calculated. This was done by multiplying the Cancer Score values for each chemical by its total release quantity (in pounds). The Relative Cancer Scores were only calculated for releases classified as air releases, as releases from stack or fugitive air made up the majority of the carcinogenic releases in this study area. The Relative Cancer Scores were calculated using the Inhalation Unit Risks (IUR) Toxicity Weights as described in the RSEI Methodology (United States Environmental Protection Agency 2019).

Statistical analysis

Pearson correlation coefficients were calculated between the nine selected Census variables before clustering; these results can be seen in Online Resource 3. All statistical analyses were done in R (Version 3.5.3) (R Core Team 2020).

Results

Comparison of residential clusters and the quantity of chemical releases across the study area

In Charette et al. (2021), seven clusters were established using Ward's hierarchical clustering from the nine, Census-derived sociodemographic factors identified as influential in our study area (Fig. 1). The clusters were named according to their most prominent traits, and these include Minority Working Class, Working Class, Wealthy Educated, Suburban, Low-SES Urban, Wealthy Working Class, and Rural. More detailed information on the clusters can be seen in Charette et al. (2021) and in Online Resource 2.

The quantity of chemicals released from TRI facilities within the seven clusters ranged from approximately 10,000 pounds (Low-SES Urban) to approximately 5,000,000 pounds (Working Class). In four of the seven clusters, TRI facilities released over one million pounds of chemicals (Table 1). These clusters, in decreasing order from the

Table 1 Top three facility and chemical releases breakdown

	Minority Working Class	Working Class	Suburban	Wealthy Working Class	Rural	Low-SES Urban	Wealthy Educated	Total
Cluster area information								
Number of facilities (n)	46	44	12	12	8	4	3	129
Chemical release data								
Quantity of chemical releases (pounds) ¹	5,327,878	6,038,163	1,799,525	475,652	2,970,262	10,043	395,285	17,020,137
Quantity of the top three chemical releases (pounds) ²	3,293,227	5,002,898	1,723,119	90,009	2,828,487	10,043	395,285	13,938,344
Percent of the top three chemical releases, by quantity	62%	83%	96%	19%	95%	100%	100%	82%
Carcinogenic chemical release quantity (pounds) ³	63,173	1,306,296	802	15,744	1,420	3,971	38,922	1,430,328
Percent of the top three chemical releases, by carcinogen release	1.2%	21.6%	0.0%	3.3%	0.0%	39.5%	9.8%	8.4%

¹Sum of the total on-site releases from all 129 facilities within the cluster

²Sum of total on-site releases for just the facilities included in the top three analysis

³Sum of total on-site releases for just the carcinogens released in the top three analysis

highest to lowest quantity of releases, are the Working Class, Minority Working Class, Rural, and Suburban clusters. Of these, the Minority Working Class cluster had 46 facilities in it, and the Working Class cluster contained 44 facilities; the Rural and Suburban clusters housed 8 and 12 facilities each, respectively.

Quantity of chemical releases and mass percentages of top three polluting facilities by cluster

The mass percentages of chemical releases from the top three polluting facilities were calculated to assess whether pollutant releases were uniform across the different clusters or if a majority of the pollutant releases were coming from a small number of polluting facilities (Collins et al. 2016). We chose to look at the top three polluting facilities because the smallest number of facilities housed within any cluster (the Wealthy Educated Cluster) was three. For mass percentages between 80 and 100%, the top three polluting facilities were responsible for a large amount of the total quantity of chemicals released in each cluster. Within both the Low-SES Urban and Wealthy Educated clusters, the top three polluting facilities contributed 100% to the total quantity of releases (Table 1); these were also the two clusters with the smallest quantity of TRI facilities located within them ($n = 4$ and $n = 3$). However, in the suburban cluster, 96% of the chemical releases originate from the top three polluting facilities; this cluster contained 12 TRI facilities, suggesting that most

of the releases from this cluster came from a quarter of its facilities. Interestingly, in the Working Class cluster, 83% of the chemical releases came from the top three polluting facilities. This cluster contained 44 TRI facilities, highlighting how a small number of polluting facilities can contribute a large percentage of the total chemical releases. Lastly, the Wealthy Working Class cluster had only 19% of its chemical releases originate from the top three polluting facilities, representing the cluster with the lowest mass percentage. This low percentage suggests that the distribution of chemical releases from TRI polluting facilities in this cluster was less skewed than the other clusters identified in this work (Table 1).

Facility Scores of top three polluting facilities by cluster

Previously, researchers have found that there might not be a clear relationship between the quantity of chemicals released by a facility and their associated chemical toxicities (Lim et al. 2010). Therefore, our analyses were extended to assess the toxicity of the chemicals released from the top three polluting facilities per cluster. To assess chemical toxicity, the Facility Score for each polluting facility was obtained from the RSEI Model; this value allows researchers to assess differences between facilities based on the toxicity of the compounds they are releasing.

Based on their elevated Facility Scores, two clusters—the Working Class and the Minority Working Class clusters—contained TRI facilities that released the most toxic compounds (Fig. 2). Of these, the cluster that contained the TRI facility with the highest Facility Score was the Working Class cluster. In this cluster, 99.7% of the total chemicals released originated from one facility, which was identified as a business park.

The Facility Score percentages from the top three polluting facilities, compared to the combined Facility Scores from all the TRI facilities, were also calculated (Fig. 3, Online Resource 4). The Facility Score percentages were calculated by dividing the sum of the Facility Scores from the top three polluting facilities by the sum of all Facility Scores per cluster and multiplying by one hundred; each percentage was calculated per cluster. These percentages ranged from 84% (Rural) to 100% (Wealthy Educated, Low-SES Urban). Based on these high percentages, the top

three polluting facilities in each of the clusters released the majority of the most toxic compounds in our study area.

Comparing the percentages of chemical releases by mass and Facility Score

For a given cluster, if the Facility Score percentage is greater than the mass percentage, this suggests that the top three polluting facilities may not have the largest outputs by mass, but the toxicity of the releases is high. This imbalance between Facility Score and the mass percentage was observed in the Minority Working Class and Wealthy Working Class clusters (Fig. 3). In the Minority Working Class cluster, the mass percentage was approximately 62%, but the Facility Score percentage was 93%. However, the imbalance between mass and Facility Score percentages was greatest in the Wealthy Working Class cluster, where the mass percentage was approximately 19%, but the Facility Score percentage was 96% (Fig. 3).

Fig. 2 Facility Scores of the top three facilities per cluster. Facility Scores were calculated by summing all RSEI modeled hazard scores for all chemicals released by each facility

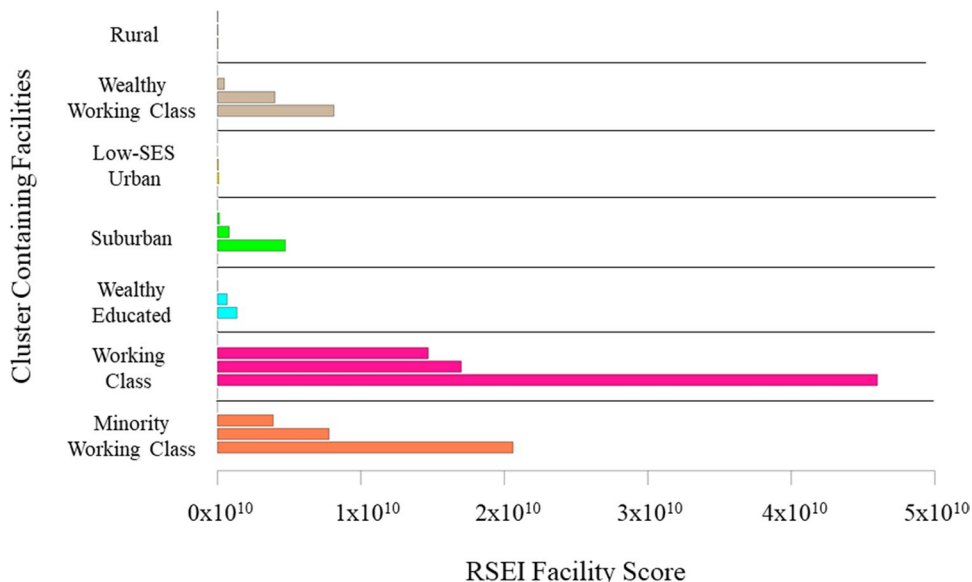
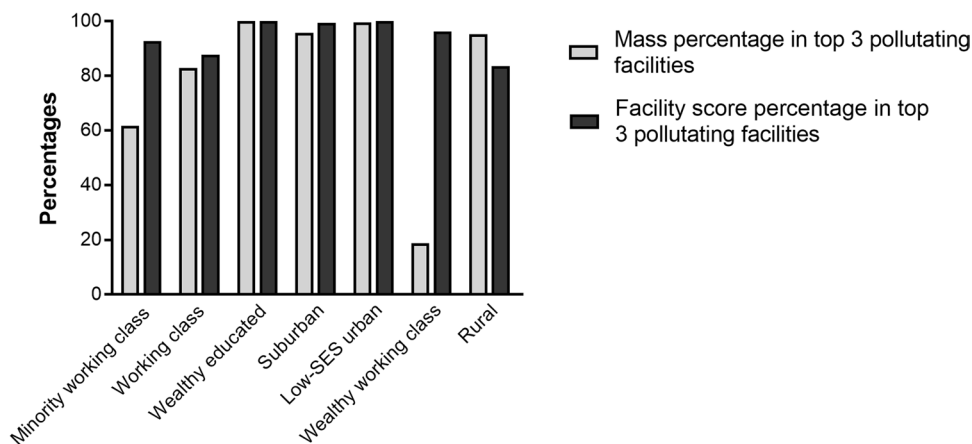


Fig. 3 The percentage of the quantity of chemicals released from the top three polluting facilities per cluster compared to the Facility Score percentage per cluster



Carcinogenic chemical releases

Since toxicity varies based on the chemicals being released, we conducted chemical-specific analyses among the top three polluting facilities, and our focus was on chemicals that were classified as carcinogenic. Twenty-one different carcinogens were released in varying amounts across the seven clusters (Online Resource 5). Dichloromethane represented the carcinogen with the greatest release; this release came from one facility within the Working Class cluster, and this was the same facility with the greatest Facility Score (Fig. 2).

The Low-SES Urban cluster had the highest percentage (39.5%) of carcinogens released within it (Table 1); this cluster only contained four TRI facilities. However, the Wealthy Educated cluster had three TRI facilities with only 9.8% of releases identified as carcinogens (Table 1), suggesting that the compounds released in this cluster are less likely to be cancer causing. When comparing the percentages of carcinogens released from the top three polluting facilities between the clusters with the greatest number of TRI facilities, large differences were found. In particular, within the Working Class cluster ($n = 44$ facilities), 21.6% of the top three polluting facility releases were carcinogens, whereas, in the Minority Working Class cluster ($n = 46$ facilities), the percentage of releases that were carcinogens was less than 2% (Table 1). This information suggests that there is an unclear and complicated relationship between the number of polluting facilities, quantity of chemical releases, toxicity of releases, and carcinogenic releases in our geographic clusters.

Figure 4 demonstrates how the quantity and toxicity of chemicals released from facilities can differ. The cluster that released the largest quantity of carcinogenic chemicals was the Working Class cluster (Fig. 4a). The carcinogenic chemical releases from this cluster totaled approximately 1.3 million pounds (Table 1), representing 91% of the total carcinogens released from the top three facilities per cluster across our study area. However, the cluster that released the chemicals of the greatest Relative Cancer Score was the Wealthy Working Class cluster (Fig. 4b). The Relative Cancer Score of the greatest release in that cluster, chromium, was valued at 1.43×10^{11} . The next greatest Relative Cancer Score, also chromium, was found in the Minority Working Class cluster and was valued at 1.83×10^{10} .

Additionally, when comparing chemicals by quantity and toxicity, some of the most toxic chemicals could be overlooked because they are released in such low quantities. For instance, when only quantity is considered, chemicals such as dichloromethane stand out; however, when toxicity is considered to determine the relative cancer risk, chromium, chromium compounds, and cobalt are a bigger risk.

Discussion

The main objective of this study was to compare the pollutant releases from TRI facilities in Upstate New York, both by quantity and toxicity. We chose this study area because the cities of Buffalo, Rochester, Syracuse, and Albany all have large concentrations of communities within them that have been identified by the New York Department of

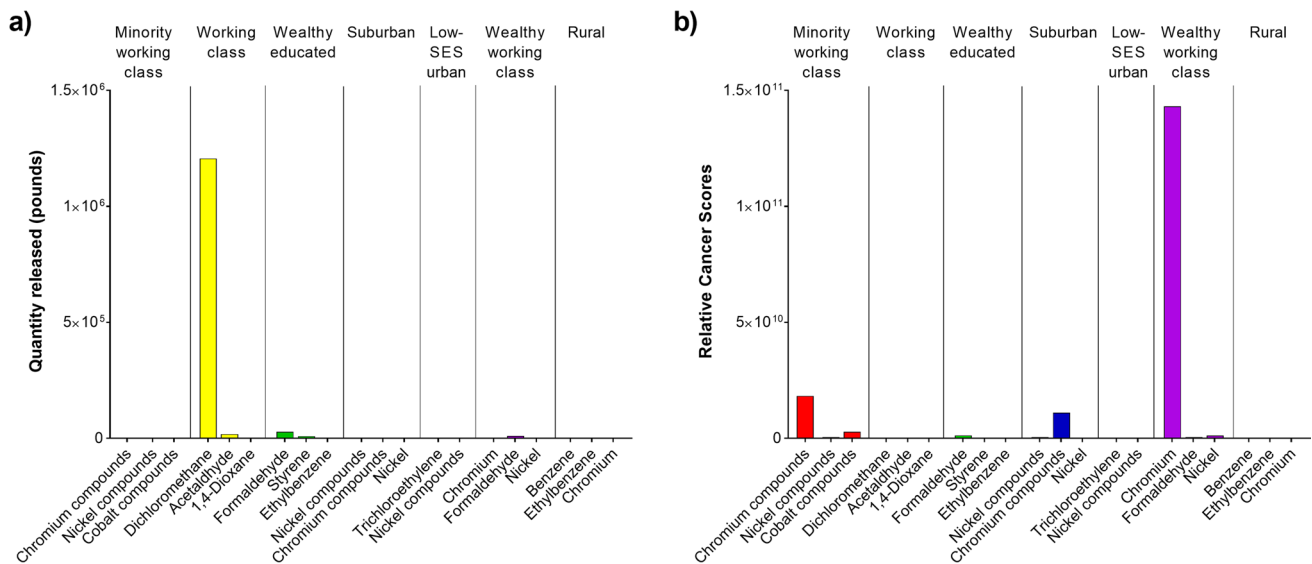


Fig. 4 **a** The top three carcinogens released in the greatest quantity per cluster (in pounds). **b** The relative cancer scores for the top three carcinogens released in the greatest quantity (in pounds) per cluster.

The toxicity weight of the chemicals was multiplied by the quantity of chemicals released (in pounds) into the air by either stack or fugitive sources

Environmental Conservation as potential environmental justice areas, although little research has been conducted in these locations (New York State Department of Environmental Conservation 2021a). A closer examination of the top three polluting facilities, with respect to the quantity of chemical releases, toxicity, and carcinogenic chemical releases, was conducted to assess how consistent the releases were across the geographic study area. The Minority Working Class and Working Class clusters had the highest quantity of TRI facilities, chemical releases, and Facility Scores. When assessing the carcinogenic chemicals released from these facilities, the Working Class cluster released the greatest quantity of carcinogens from its top three polluting facilities, but the Low-SES Urban cluster released the greatest percentage of carcinogens overall. This study demonstrated how a more in-depth analysis of the chemicals released from TRI facilities could aid in addressing and understanding the potential issues of inequality faced by the communities surrounding these hazardous waste facilities.

Top three polluting facilities (based upon Facility Score) per cluster analysis

The top three polluting facilities per cluster were investigated in this study. In all cases, except two, the quantity of chemicals released from the top three polluting facilities accounted for at least 80% of the total chemical releases for each cluster (Table 1). In the Minority Working Class cluster, 62% of chemicals were released from the top three polluting facilities (Table 1). This lower percentage could have to do with the greater number of polluting facilities located in this cluster ($n = 46$ facilities). In the Wealthy Working Class cluster, only 19% of chemical releases were emitted from the top three polluting facilities (Table 1). This could be because the facility that had the greatest chemical releases, which accounted for approximately 64% of the total chemical releases for the Wealthy Working Class cluster, was not included in the top three polluting facilities analysis because of the facility's low Facility Score.

Multiple researchers have investigated the top polluting facilities per region, or industry class, and have concluded that a small number of polluting facilities are often responsible for a large amount of pollutant releases (Grant et al. 2013; Collins et al. 2016, 2020; Galli Robertson and Collins 2019). Freudenburg (2005) was the first to describe this uneven distribution of pollution production using the term "disproportionality" (Freudenburg 2005). He showed that these patterns are not necessarily new, finding evidence of disproportionality as far back as 1993. That year, the chemical releases from two companies accounted for 14% of all toxic releases for the TRI database. Freudenburg also noted that these polluter outliers, despite their large chemical outputs, fail to out-perform other companies with regard

to employment ratios or revenue. Taken together, the same two companies accounted for only 0.09% of the national workforce and had a revenue equal to six-tenths of a percent of the Gross National Product that year, highlighting how the pollution they generate is not offset by societal benefit. More recent observations of disproportionality have also been reported by Grant et al. (2013). Energy-released carbon dioxide outputs from the world's energy sector were measured to determine if any one nation was emitting more than their "fair share" of pollutants. The twenty countries with the greatest overall greenhouse gas emissions were responsible for 82% of the world's electricity-related carbon dioxide emissions. Overall, the group concluded that electricity-related carbon dioxide emissions from the top 5% of polluting power plants made up massive shares of the country's total emissions. The results of our study show that the problems of disproportionality that were occurring long ago are still happening now.

Facility location and toxic chemical releases

After the RSEI chemical weighting scheme was chosen for this work, the RSEI Facility Scores for all the facilities in the study area were obtained. By incorporating the toxicity data, a consistent relationship between the number of facilities present within each cluster and the Facility Scores of each cluster was observed. For example, the Minority Working Class and Working Class clusters had the greatest number of facilities (Table 1) and the greatest Facility Scores (Fig. 2). The reverse of this pattern also holds in that the Wealthy Educated cluster had the fewest number of facilities and some of the lowest Facility Scores. The Wealthy Educated cluster, which is comprised of residents of a higher socioeconomic status (Charette et al. 2021), had the smallest number of facilities (Table 1) but had higher Facility Scores than the Rural and Low-SES Urban clusters (Fig. 2), the latter of which was comprised of residents of a lower socioeconomic status (Charette et al. 2021). These results appear to be an anomaly since it has been well documented that more socially disadvantaged individuals often take the brunt of industrial chemical exposures (Sicotte 2010; Chakraborty et al. 2014; Rosofsky et al. 2018; Flores et al. 2020). While the Wealthy Educated Cluster had one of the lower quantities of chemical releases, the Facility Scores seen in this cluster suggest the chemicals being released from its facilities had the potential to cause more harm than the chemicals released from facilities in other clusters. The disparity between the results of this paper and the evidence within the literature prompted a quantity-based versus toxicity-based investigation into how the quantity of chemicals released from facilities within a cluster may be related to Facility Scores.

In comparing the quantity-based and toxicity-based results, no clear pattern emerged. For example, the Minority

Working Class and Working Class clusters had the greatest quantities of chemical releases as well as the greatest Facility Scores (Table 1, Fig. 2), suggesting their bulk releases were some of the most ubiquitous and toxic. However, the Rural cluster, which is the cluster with the next greatest quantity of chemical releases (Table 1), had the lowest Facility Score. Moreover, the Suburban cluster, which had the next lowest quantity of chemical releases (Table 1), had greater Facility Scores than those in the Rural cluster. This discrepancy between quantity- and toxicity-based results has been documented before in other work (Lim et al. 2010; Taylor et al. 2020). The importance of considering toxicity is explained best in Bouwes et al. (2001), where the authors state that the toxicity of TRI chemicals varies so greatly that a single pound of some of the most toxic chemicals is toxicologically equivalent to one hundred million pounds of the least toxic chemicals.

Mass and Facility Score percentages

Both the mass and the Facility Score percentages of the top three polluting facilities were examined in this work (Fig. 3). The top three facilities were evaluated more closely because prior research has shown that a small number of facilities within industry sectors have the potential to release a majority of the toxic releases within specific industries (Collins et al. 2016, 2020). In almost all clusters, the Facility Score percentage was greater than the mass percentage. This trend has been observed by multiple researchers across different studies (Dunn 2009; Luo and Li 2021). In the current work, the only cluster to not follow this trend was the Rural cluster. In the Rural cluster, the mass percent was 95%, whereas the Facility Score percent was 83% (Fig. 3, Table 1). This discrepancy was most likely due to the fact that in the Rural cluster, one facility in the top three polluting facilities released 95% of the total chemical releases; however, many of the chemicals released from this facility were not as toxic as others, which led to the overall lower Facility Score percentage.

In the Wealthy Working Class cluster, the difference between the mass percent and the Facility Score percent was profound; the mass percent was 19% and the Facility Score percent was 96% (Fig. 3, Table 1). This indicates that 96% of all potential risk in the cluster comes from only three facilities. There are two potential reasons why this could happen. First, it is possible that one of the facilities in the Wealthy Working Class cluster releasing the greatest quantity of chemicals was not included in the top three polluting facilities analysis (due to its lower Facility Score and less toxic releases). A second alternative reason could be that the Facility Scores for the top three polluting facilities within this cluster were 2 to 3 orders of magnitude greater than most of the other Facility Scores within this cluster. This was

a stark example of not only the difference between quantity-based and toxicity-based methods, but also super-polluters. Regardless, this is not the first study where this trend was observed. A similar finding was seen in Abel (2008). Abel developed a TRI case study of air pollution exposure risks across metropolitan St. Louis and used an exposure risk characterization to aid in the determination of whether the area was experiencing environmental injustices. Abel found that, of the 319 facilities hosted by the St. Louis area, when four facilities were combined, they accounted for one-fifth of the entire region's air pollution exposure burden. Additionally, twenty of the 319 plants produced 77% of the region's overall risk. This demonstrates not only how toxicity can play an important role in understanding environmental inequities, but also how unevenly these inequities can be spread out among facilities in certain areas.

Carcinogens

An in-depth analysis looking specifically at the carcinogens released from the top three polluting facilities, including the percentage of carcinogens released per cluster, as well as the top three carcinogens released per cluster, was performed. Additionally, the analyses focused on carcinogens because the RSEI model focuses on carcinogens along with chronic toxic effects (United States Environmental Protection Agency 2019).

The cluster with the highest percentage of carcinogenic releases was the Low-SES Urban cluster; approximately 40% of the chemical releases from the top three polluting facilities in this cluster were considered carcinogenic (Table 1). The next highest percentage of carcinogens was released in the Working Class cluster, where approximately 22% of the releases were classified as carcinogenic (Table 1). The Low-SES Urban cluster was classified as housing residents with an overall lower level of socioeconomic status, and the Working Class cluster was classified as housing a greater proportion of residents working in non-managerial positions (Charette et al. 2021).

The facilities in the study area releasing the lowest percentages of carcinogens were in the Suburban (0%), Rural (0%), and Minority Working Class (1%) clusters (Table 1). The Suburban and Rural clusters had none of their releases classified as carcinogenic (Table 1), and both clusters house relatively low numbers of polluting facilities. The anomaly in this situation is the Minority Working Class cluster, which houses 46 facilities, had over three million pounds of chemicals released from its top three polluting facilities (Table 1), and was classified as having a relatively high percentage of residents working in non-managerial positions (Charette et al. 2021); however, the percentage of carcinogens released from the top three polluting facilities was only 1%. The main reason for this discrepancy may be because, from the top

three polluting facilities, one facility released over three million pounds of chemicals alone, but only 61,000 pounds of those chemicals were classified as carcinogenic. The other two facilities combined released 2000 pounds of chemicals, 1500 of which were considered carcinogenic, leading to a total of just over 62,000 pounds of chemicals being considered carcinogenic for three facilities releasing over three million pounds of chemicals. This inequality shows the complex relationship between the quantity of chemicals released and the quantity of chemicals that pose a threat to human health.

In the analyses of the top three carcinogens released per cluster from the top three polluting facilities per cluster, the carcinogens present in the greatest quantities were dichloromethane, formaldehyde, and acetaldehyde (Fig. 4a). The carcinogens with the greatest Relative Cancer Scores were chromium, chromium compounds, and cobalt compounds (Fig. 4b).

Dichloromethane, also known as methylene chloride, was released in the highest quantity, totaling 1,269,700 pounds from one facility within the Working Class cluster (Fig. 4a). Dichloromethane is typically used as a solvent, but it has also been used in the production of paint strippers and removers, in the manufacture of drugs and pharmaceuticals, and in the production of soft polyurethane foams (Agency for Toxic Substances and Disease Registry 2000; Cooper et al. 2011). Another common use for dichloromethane is in the production of soft polyurethane foams (Dekant et al. 2021). With respect to toxicity, short-term exposures to high concentrations of dichloromethane have been associated with drowsiness and dizziness, and these exposures, in very high concentrations, can result in unconsciousness and coma (Dekant et al. 2021). Longer-term exposures to dichloromethane have been associated with an increased incidence of childhood cancer (Park et al. 2017) and malignant liver and lung tumors in mice (Dekant et al. 2021). The International Agency for Research on Cancer has identified dichloromethane as a category 2B carcinogen (possibly carcinogenic to humans) (Dekant et al. 2021).

Formaldehyde was released from two facilities, one in each of the Wealthy Educated and Wealthy Working Class clusters (Fig. 4a). Formaldehyde is most commonly used in the manufacturing industry to produce formaldehyde resins that are used in particleboard products (Agency for Toxic Substances and Disease Registry 1999). Multiple inquiries have been posed about the health effects of exposure to formaldehyde, both in industrial and everyday life (Li et al. 2017; Seals et al. 2017; Ge et al. 2020). Li et al. (2017) conducted a study looking at the effects of formaldehyde exposure on mice and found that formaldehyde exposure could induce inflammation of the airways and bronchial hyper-responsiveness. In human populations, Seals et al. (2017) found a 1.3-fold increased risk of amyotrophic lateral sclerosis (ALS) related to occupational formaldehyde exposures.

These two studies demonstrate the toxicity of exposures to formaldehyde, indicating the need for strong safety practices and increased awareness.

Chromium was the chemical with the greatest Relative Cancer Score in the study area (Fig. 4b, Online Resource 5), which was followed by “chromium compounds.” “Chromium compounds” are defined by the US EPA to encompass all unique substances that contain chromium as part of that chemical’s infrastructure (United States Environmental Protection Agency 2018), whereas “chromium” is the chemical in its metallic form. Studies have been conducted looking at the effects of chromium on human health, but many studies focus primarily on hexavalent chromium due to its chronic effects (Wise et al. 2010; Sciannameo et al. 2019; Oginawati et al. 2021). Wise et al. (2010) conducted a study examining the genotoxicity and cytotoxicity of zinc chromate, barium chromate, lead chromate, and sodium chromate in human bronchial cells. The group found that all four compounds induced a concentration-dependent decrease in relative cell survival as well as a concentration-dependent increase in the amount of DNA double-strand breaks. The results of the Wise et al. (2010) study showed the adverse health effects that excessive chromium compound exposure can have.

Limitations and strengths

The present study had several limitations. First, the data was taken from the 2000 US Census as opposed to the 2010 or 2020 US Census because block group level data was not available for the chosen demographics in the most recent US Censuses (Mirowsky et al. 2017; United States Census Bureau 2019). However, data from the TRI program was also taken from the year 2000 to provide consistency across the study. Next, there are limitations with the databases used. With the TRI program, there is a minimum reporting limit, meaning that smaller facilities are exempt from reporting their releases, and the data from this program relies on self-reported information (Wilson et al. 2012; United States Environmental Protection Agency 2021d). The RSEI program takes its data from the TRI program, so any limitation related to TRI facilities impacts the values obtained from the RSEI program. Finally, this study did not consider the transport of chemicals across block groups and only considered the sociodemographic factors of the cluster the facility lies in. Thus, it is possible that a facility could be located close to the border of a neighboring block group and not be counted in this analysis. This was done to ensure we were looking at each cluster evenly and only examining the top three facilities in that cluster.

There are also several study strengths. First, this study examines both quantity- and toxicity-based outcomes (Lim et al. 2010; Setton et al. 2015; Luo and Li 2021). While other studies have been completed using both these outcomes,

this is the first study to compare both quantity- and toxicity-based outcomes in the Upstate New York area. Upstate New York has not typically been a focus of this type of work before (Hill et al. 2018). However, assessing disproportionality in this geographic region is important, considering that Buffalo, Albany, Rochester, and Syracuse, NY, have all been credited as some of the most impoverished cities in New York State (United States Census Bureau 2020). Finally, the study aided in demonstrating the usefulness of the RSEI Model as a tool for communication to communities surrounding these hazardous waste facilities.

Conclusions

In conclusion, a novel clustering technique was utilized to establish seven unique residential clusters in Albany, Erie, Monroe, and Onondaga Counties. Within these clusters, all TRI facilities with EPA-provided Facility Scores were geocoded to determine if any trend was present in both the quantity of chemicals released, as well as the toxicity of the releases. The top three Facility Scores were examined more closely to look specifically at the chemicals being released. This was justified as super-polluter facilities have been the subject of multiple studies, and the same type of uneven distribution was observed in this study area. The Minority Working Class and Working Class clusters had the highest and most consistent Facility Scores, but the results examining carcinogens released within these two clusters were inconclusive. Looking at the sociodemographic makeup of the clusters and their subsequent chemical releases, the overall results of this study appear to support those seen in many environmental inequity studies. Additionally, upon examining the quantity and toxicity of chemicals released from the facilities in the study areas, just assessing the quantity of chemicals released from a facility does not adequately address the issues being faced by the surrounding communities. Future work on this topic can include expanding the geographic area being studied to assess whether the same trends are observed in different areas and taking into account the fate and transport of the chemicals across block groups and clusters.

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Author contribution Amanda Charette: methodology, Formal analysis and investigation, writing—original draft preparation, writing—review and editing.

Dustin Hill: formal analysis and investigation, writing—review and editing

Mary Collins: writing—review and editing

Jaime Mirowsky: conceptualization, methodology, writing—review and editing, funding acquisition, supervision

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon request.

Code availability All analyses were done using RStudio version 3.5.3. All code used in creating images is available from the corresponding author upon request.

Declarations

Conflict of interest The authors declare no competing interests.

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