8-2018

A Visual Data Analysis of the Toxics Release Inventory

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A VISUAL DATA ANALYSIS OF THE TOXICS RELEASE INVENTORY

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Environmental Engineering and Earth Sciences

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by
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August 2018

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ABSTRACT

The Environmental Protection Agency's Toxics Release Inventory (TRI) is a collection of data detailing the way hazardous chemicals are handled in industrial facilities. By requiring certain manufacturing facilities to report releases, the EPA offered the public unprecedented access to environmentally relevant data. Since its inception in 1986, the TRI has grown and changed both in chemicals and industries monitored. This thesis uses the data visualization platform Tableau, publicly available yearly TRI reports, and Life cycle impact assessment methodology to create a tool which 1) improves upon previous analyses of the TRI dataset, 2) offers an analysis based on previously underexplored environmental impacts, and 3) creates a simple online tool for communities, industry, and government to use to better identify and target problem areas.

ACKNOWLEDGEMENTS

Thank you to my committee, Dr. Carraway, Dr. Dale, and Dr. Ladner for supporting me through the E3 grant, as well as providing insights into my project, gathering data, and directing the research into the quagmire that is Toxics Release Inventory data.

Also, a big thank you to John Sherwood for introducing me to Tableau and his willingness to allow me to bounce ideas off him from across the office.

Thank you, Margaret Thompson, for being a friend and mentor and supporting my interest in Environmental Policy.

Thank you, E3SA research group members, current and former, for your academic interest and sharp minds.

Lastly, thank you to my friends and family who are always a call away and always supportive.

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1 INTRODUCTION

1.1 SOUTH CAROLINA E3: ENERGY-ECONOMY-ENVIRONMENT

The South Carolina Economy, Energy, Environment (SCE3) program began as a Pollution Prevention (P2) grant from the Environmental Protection Agency (EPA). It is a collaboration between partners Clemson University, Duke Energy, South Carolina Manufacturing Extension Partnership (SCMEP), and South Carolina Department of Health and Environmental Control (DHEC). SCE3 uses community resources to provide technical assistance to small- to medium-sized manufacturers in upstate South Carolina in the form of energy, waste, and lean business audits. The program helps drive sustainable manufacturing by reducing energy and material waste while increasing efficiency and productivity. Pursuant to SCE3's waste reduction mission, this research explores trends in industrial waste management, including pollution prevention practices and changes in national hazardous waste policy.

1.2 MOTIVATION AND GOAL

SC E3 provides facility-level technical assistance to manufacturers, which requires direct contact with individual companies. This hands-on approach is useful when assisting manufacturers who reach out for auditing and benchmarking. However, without site visits from trained auditors or an in-depth understanding of yearly releases, companies may not fully understand how their facility compares to others in the industry, geographic area, or type of chemical processing. The goal of this project is to fill such

knowledge gaps and provide a national-level, impact-based view of chemical release trends, through the creation of an interactive online tool. This tool will provide legislators, facilities, industry groups, and various levels of government the opportunity to track releases geographically and over time to identify trends in hazardous chemical use and release without inside knowledge of any specific facility or industry.

2 BACKGROUND

2.1 EXISTING DATA – TOXICS RELEASE INVENTORY

In December of 1984, approximately 40 metric tons of methyl isocyanate (CH_3NCO) gas was accidentally released at a Union Carbide plant in Bhopal, India. The resulting cloud of gas killed between 2,000 and 4,000 people in the city and many more were hospitalized (Broughton, 2005). The Bhopal incident is still considered to be the worst industrial accident in history. Public concern after this event and several smaller accidents in the United States was enough to spur lawmakers into action. In 1986, Congress passed the Emergency Planning and Community Right-to-Know Act (EPCRA) (Koehler, 2007). This act sought to prepare industries and communities for such disasters and reduce the likelihood of their occurrence through planning and regulation of hazardous chemicals. If community members are informed about industrial actives, they can exert influence over facilities that may be releasing toxic chemicals to their local environments. Thus, a new planning, reporting, and emergency notification system emerged (EPA 1986).

Under Section 313 of EPCRA the EPA created a list of hazardous chemicals to be tracked by the sitting administrator. Facilities which handle the listed chemicals above threshold amounts, unique to each chemical, are required to report use of those chemicals to the EPA via a special reporting document called "Form R," which can be found in Appendix A. This form identifies the company, its location, industry classification, the

chemical and its method of management. These management categories are informed by EPA's Pollution Prevention Hierarchy and include direct releases to air, water, or land, as well as waste management categories such as "on-site recycling processes," and "off-site treatment" (EPA 2017). By collecting reports of these metrics, EPA built what is known as the Toxics Release Inventory (TRI). The data exist as series of spreadsheets, yearly reports, and an online tool that provides the public with general information on facilities and industries that handle hazardous chemicals. Figure 1 is a visual timeline of the TRI program and details changes and updates to reporting.

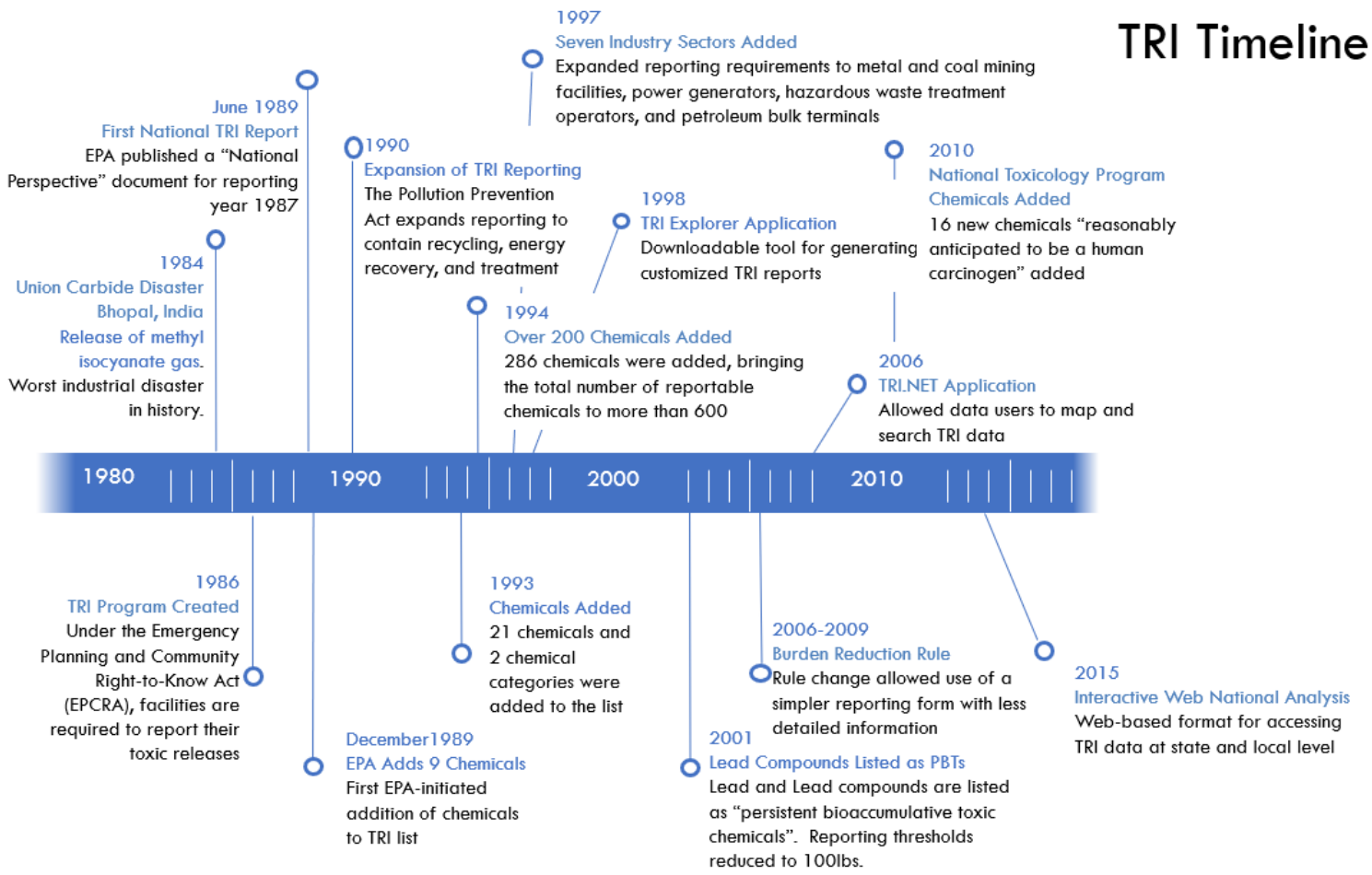

Figure 1.1 A Visual Timeline of the TRI Program

2.2 TRI Successes

The TRI program offers an unprecedented amount of data to the public. In a way that no public policy had done previously, it put power in the hands of citizens by creating a transparent system of pollution reporting.

2.2.1 A Novel Approach

Often cited as some of the most successful environmental legislation, TRI is at its simplest level, a collection of data detailing legal releases, transfers, treatment, and recycling of hazardous chemicals. Manufacturing facilities acquire permits for each chemical handled and report their use as required by law. EPA rarely inspects reporting facilities and emissions are often estimated rather than stringently measured. This variety of informal regulation was relatively novel, and unexpectedly successful. Instead of fining and penalizing companies for non-compliance, TRI relies on transparency. Reported releases become public record and can serve as leverage for community activists or government agencies wishing to apply pressure on manufacturers to change their behavior. Its success hinges on free and open access to data and the ability of outsiders to identify trends and use them to influence corporations, not to mention the honesty in company reporting. In a 2000 EPA press release, then Vice President Al Gore said:

> *Putting basic information about toxic releases into the hands of citizens is one of the most powerful tools available for protecting public health and the environment in local communities. That is why this Administration has*

> *dramatically expanded the public's access to this vital information. Citizens now have more information than ever at their fingertips to help protect their communities, their health and their children's health. (EPA Press Release, 2000)*

Simply measuring the release of toxic chemicals seems to be the first step in achieving reductions. In 1995, the 9th year of the program, the EPA reported a decrease in total releases and transfers of 45% since 1988 (Fung and O'Rourke, 2000). While the reduction reported cannot be completely attributed to TRI data collection, its availability certainly influenced industry action on improving pollution control technologies and process efficiency.

2.2.2 Measured Success

Other studies, such as that performed by Koh et al. (2016) seem to confirm that the reduction trend which began in the early years of TRI continued between 1999 and 2009. Using an input-output structural decomposition analysis (SDA), the authors were able to combine the TRI dataset with information about population growth, consumption of goods and services per capita in the US, and changes in input mix (use of domestic or imported materials). The resulting analysis identifies drivers of the Toxicological Footprint (TF) within the US economy. The authors measured a 39% decrease in TF between 1999 and 2013 due to improvements in production efficiency, despite increases in both consumption volume (8%) and population (10%), which would ordinarily increase the TF. It is reasonable to attribute this decrease to a collective transition to cleaner methods of production across various manufacturing industries. Interestingly, the authors also measured a 14.1% increase in TF between 2009 and 2013, due to a combination of factors including economic growth during recovery from a recession, an

increase in consumption volume, and population growth, which combined to nullify a measured 4% improvement in emissions intensity. In general, the TRI and associated EPA programs encouraging reduction activities have driven increases in production efficiency and subsequent decreases in emissions intensity – in this case, the ratio of chemical emitted per unit of product produced.

Additional benefits of the TRI include its ability to flag particularly toxic chemicals, including those known to cause cancer. Between 1995 and 1999, emission of chemicals designated as "carcinogens" decreased 16%, while total releases decreased only 7% (Graham and Miller 2001). Not only does the TRI system encourage reduction of toxic chemicals through data transparency, it is structured to identify and reduce the most toxic of these first, based on simple data.

2.3 TRI Challenges and Failures

2.3.1 Data Accuracy

Despite its apparent success, the TRI is not a one-size-fits-all solution to production waste. As a result of its light regulation on industry, the inventory itself contains mistakes, estimates, and an occasional data gap. In the program's first year, the EPA estimated that 10,000 of about 30,000 facilities required to report failed to do so (Wolf 1996). A 1990 General Accounting Office (GOA) study of the program found non-reporting to be a significant issue that stemmed from "inefficient strategies to identify non-reporters," and the "absence of explicit authority under [EPCRA] to inspect facilities for compliance" (GOA 1990). Additionally, choice of reporting category, often left up to

the discretion of the facility manager, can affect results. "Paper changes," in which the disposal category is changed from one year to the next, were found to account for more than half of reductions between 1991 and 1994 in one study (Natan and Miller, 1998). By "redefining on-site recycling activities as in-process recovery," facilities avoided the necessity of reporting to a TRI waste management category. The result does not reflect a physical change in the manufacturing process, but to an outside party, and without additional information, it could appear to be a reduction.

This, however, is not to say that the TRI is not a useful data set for environmental scientists, industry professionals, lawmakers, and community members. Despite its flaws, the inventory still represents the most comprehensive gathering of hazardous chemical data available. Graham and Miller (2001) call it "an evolutionary bridge between familiar national policies that treated information as a public right and emerging strategies that employ information as regulation." Despite data issues in the early years of the program, the EPA provides a series of checks on data accuracy and completeness. EPA's data quality group provides guidance during the reporting period through an online tool and a reporting "hotline" (TRI Data Quality 2018). Unusual release characteristics such as large increases or decreases from the previous year or increases of releases of persistent bioaccumulative toxics (PBTs) are flagged and the facilities in questions are contacted.

2.4 Existing Models and Tools

2.4.1 TRI National Analysis

In the age of big data, we have access to even more information than VP Gore spoke about 18 years ago. TRI data are available to anyone with internet access, as is EPA's TRI National Analysis. The TRI National Analysis "summarizes recently submitted TRI data, trends, special topics, and interprets the findings from the

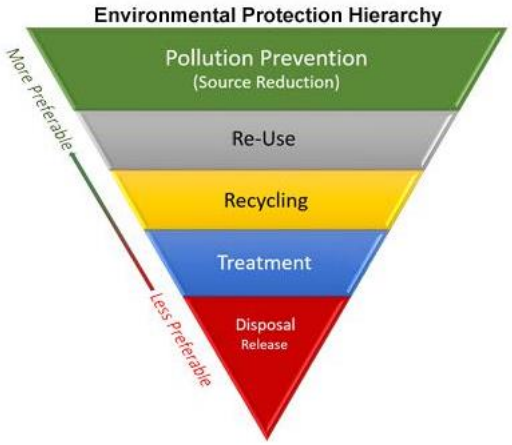

Figure 2.1 Hierarchy of Environmentally Prefereable Methods of Waste Management (EPA)

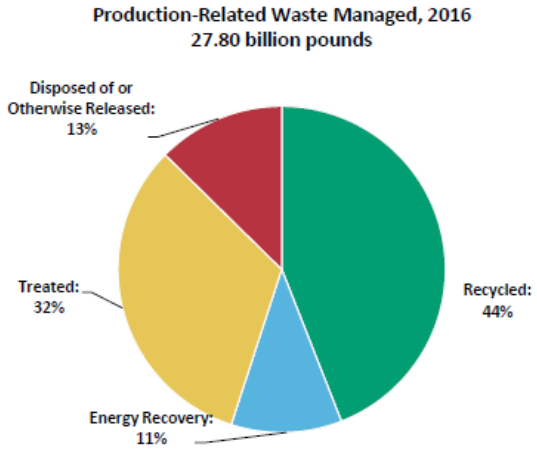

Figure 2.2 Breakdown by Method of Hazardous Waste Managed in the US in 2016 (TRI National Analysis 2016)

perspective of EPA's mission to protect human health and the environment" (EPA, 2016). The Pollution Prevention Act of 1990 the chemicals managed are broken down into categories and arranged hierarchically by environmental preferability, as shown in Figure 2.1. It begins with source reduction, which deals with preventing hazardous by-products from being produced, followed by methods for managing hazardous material after it is created.

Source reduction is "any practice that reduces, eliminates, or prevents pollution at its source" (EPA 2018). The name implies that the waste is never produced, for example by adjusting a process so that non-toxic chemicals are used in place of toxic ones. EPA considers source reduction the most preferable option.

Recycling, the next most preferable method of waste management, is any process that allows a chemical to be "used or reused, [or] reclaimed". Reclaimed materials are recovered as a useable product or regenerated to again become an input for a process. Used or reused materials are either used as an ingredient to make a product or are used as an "effective substitute for a commercial product." (EPA 2017)

Energy Recovery is technically a subset of recycling, but instead of a material becoming a feedstock for additional processes, the substance is combusted for heat or combined heat and power. For example, the data shows that hundreds of millions of kilograms of ethene are combusted on-site annually at chemical manufacturing plants in the US. Using waste ethene as a heating fuel helps a facility reduce costs and environmental impacts of bringing in additional heating sources.

Treatment constitutes a process that "modifies the chemical properties of the waste, for example, through reduction of water solubility or neutralization of acidity or alkalinity" (Glossary of Environment Statistics 1997).

Release, as its name implies, refers to any hazardous chemical that is emitted without additional treatment or processing. It can be a purposeful release from a stack, a fugitive

releases from leaks, direct discharges to surface water, or land releases which include underground injection, surface impoundments, or landfills.

These categories make up the basis for claims of improvement; reduction in less favorable categories and shifts to a more preferable category are seen as strides forward, as they certainly should be.

However, not all chemical releases are created equally. TRI data are reported in terms of pounds of chemical, and the National Analysis is produced using these same metrics. For example, the pesticide Cyfluthrin has a LD_{50} of 380 mg/kg for rats is compared to a less toxic compound like methanol, with a LD_{50} of 5628 mg/kg (Cyfluthrin and Methanol MSDS). Thus, for the rat fatality endpoint, a pound of Cyfluthrin is nearly fifteen times more potent than a pound of methanol. Cyfluthrin is also highly toxic in the aquatic environment. Further analysis will show that while methanol has the potential to cause damage to ecosystems, it is five orders of magnitude less toxic in freshwater than Cyfluthrin (TRACI 2002). In terms of production scale, it may be easier to reduce releases of methanol and its history of reduction may be found in the TRI data. Additionally, because toxicity data are not included in the analysis, reductions may appear to be more significant without adjustment for the chemical's toxicity. A better understanding of the relationship between mass and toxicity is important for facilities to understand when choosing chemicals to target for reduction.

Figure 2.2 shows the fate of TRI chemicals for the calendar year 2016. When viewed strictly in terms of mass, 27.80 billion pounds of waste appears to be a large

amount, but absent toxicological data, the importance of the management cannot be effectively quantified. This is not to say that the National Analysis is not an important tool. It is effective in communicating trends in waste management, information comparing industry sectors, and increases or decreases of specific chemical use. It presents an accessible tool to businesses, local, state, and federal government, interest groups, and citizens so that they may better understand the chemicals used in their industries, constituencies, and communities. The availability of this data assists with emergency planning, lobbying, exerting public pressure on facilities, and identifying needs and opportunities for source reduction (Fung and O'Rourke 2000). However, it does little to directly inform risk-based decisions.

2.4.2 Risk-Screening Environmental Indicators model.

Similar to the TRI National Analysis, EPA's Risk-Screening Environmental Indicators (RSEI) model intends to make hazardous chemical release data accessible to the public. Unlike the National Analysis, or interpretation of raw TRI data, the RSEI method uses toxicity and chemical transport models to give "a screening-level, risk-related perspective for relative comparisons of chemical releases" (EPA 2018). Using the model, it is possible to compare chemicals based on toxicity rather than mass alone. Although the model does not estimate actual risk to individuals, it performs an important

function: it links empirical data with science-based, environmental fate and transport models for public consumption.

The EPA hosts a user-friendly, web-based model which allows the user to sort through TRI data using various metrics, including region, chemical, industry, and individual facility. For each of these categories, EPA defines risk as measured by "RSEI Score," a "unitless measure that is *not* independently meaningful, but is a risk-based estimate that can be compared to other estimates calculated using the same method (RSEI Methodology, p. ES-7)." RSEI leverages EPA methodologies for measuring toxicity, including the Integrated Risk Information System (IRIS), and chooses toxicity data based on a hierarchical system, opting for EPA and consensus data sources over others. In addition to toxicity data, RSEI successfully introduces geospatial, meteorological, and environmental fate and transport elements using an air dispersion model AERMOD (EPA Support Center for Regulatory Atmospheric Modeling) and the National Hydrography Dataset (US Geological Survey). This coupled approach allows for the public to increase their awareness of the types of chemicals released by TRI facilities, as well as the role that climate and geography play in their transport.

Table 2.1 Description of Results from RSEI Model, EPA's RSEI Methodology, p. ES-7

Description of RSEI Results

Risk-related results (scores)	Surrogate Dose x Toxicity Weight x Population
Hazard-based results	Pounds x Toxicity Weight
Pounds-based results	TRI Pounds Released

Table 2.1 shows the three types of results gained from RSEI. Clearly, at each stage complexity of information increases, and the model becomes more useful for certain purposes. Pounds-based results are similar to information from the National Analysis with the key improvement being that RSEI data are coupled with an environmental fate and transport model. Hazard-based results expand upon the mass-based data by adding toxicity weighting. This is the key to establishing data that are comparable between different chemicals. Finally, the risk-related results multiply the surrogate dose – the concentration that is to be expected in ambient air or drinking water – by the toxicity weight and finally a population factor. While it is not specifically dedicated to evaluating trends in toxic releases, nor does it quantify risk, nor provide metrics on ecosystem damage, RSEI provides an easy-to-use platform backed by real-life toxicity data, making it a valuable tool for addressing pollution.

2.5 CONCEPTUALIZING AN IDEAL TOOL

An ideal tool fills methodological gaps in the National Analysis and RSEI methods as shown below in Table 2.2. Such a tool addresses the lack of toxicity considerations in the National Analysis, while providing a quantifiable impact-based assessment of environmental and human health effects to contrast with the risk-based RSEI model. Risk-based models like RSEI account for chemical toxicity, expected exposure dose, and population. RSEI specifically calculates a "risk score" which can be used to compare exposure to one or more chemicals. Essentially, it ranks the likelihood of a person in a location with set ambient air characteristics to experience various negative health consequences due to chemical exposure. Because this type of model is anthropocentric, it focuses only on chemicals which impact human health, whether through chronic or carcinogenic effects. Impact-based models seek to link chemical

Table 2.2 - Existing Reports Utilizing TRI Data

Yearly Analyses of the Toxics Release Inventory

Report	TRI National Analysis	Risk-Screening Environmental Indicators
Description	Mass-based release trends	Risk-based model using EPA IRIS
Deficiencies	No connection of chemicals to impacts	Lacks ecological considerations
	Limited scope and timeline	Calculates aggregated Risk "Scores" for comparison only

releases to a specific endpoint, or impact. While RSEI calculates a risk score to provide a basis of comparison, the score represents an aggregate risk to human health and does not provide information on type of health hazard which could be expected as a result of exposure to a certain chemical. An impact-based tool addresses multiple types of impacts. Given a specific discharge of a chemical to a chosen media, an impact-based model could predict, to some degree of accuracy, its effect on plants and animals in the environment or environmental quality.

The ideal tool would leverage the advantages of the breadth of data provided by TRI, the transport and exposure pathways utilized in the RSEI model and incorporate an impact-focused component to quantitatively evaluate the consequences of releases in terms of measurable environmental effects such as toxicity to organisms or health hazards for humans. The tool also emphasizes utility; it provides instant visualizations based on geographic location, chemical, industry, and specific impact. Meeting these goals requires a number of important components. The ideal tool combines the TRI data, specifying facility-level data, detailed explanations of industry codes, a protocol for evaluating chemical impact on the environment, and a visualization program able to read and sort large amounts of chemical and industrial data. The convergence of these constituent parts would allow a person unfamiliar with the TRI system and no knowledge of manufacturing to sift through historical and scientific data to find and identify important chemical trends.

2.6 Developing the Ideal Tool

The first step to developing an impact-based tool requires selection of impact categories and a method for relating chemical releases to these impacts, which will be discussed later. We assume that the TRI data set can be considered an inventory of physical flows, in this case, elementary chemical flows into the environment. Under this assumption, it is possible to use the framework of life cycle assessment (LCA), specifically life cycle impact assessment (LCIA), to evaluate the environmental consequences of the release of hazardous chemicals to the environment. To understand the principles of impact assessment and how they can play a role in creating a useful tool, it is important to understand the basics of LCA.

2.7 Introduction to Life Cycle Assessment

2.7.1 Basic Life Cycle Assessment

Life cycle assessment (LCA) is a practice that evaluates environmental impacts of a product or system over its life cycle. It has been practiced in various forms for many years, but the process was formalized under ISO 14040/44 standards. It can be thought of as a tool to track a product from "cradle-to-grave" and tally its environmental impact during those phases (LCA Principles and Practice 2006).

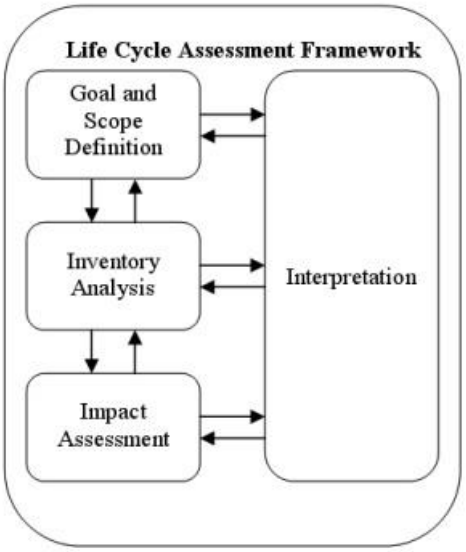

Figure 2.3 Phases of an LCA (ISO, 1997)

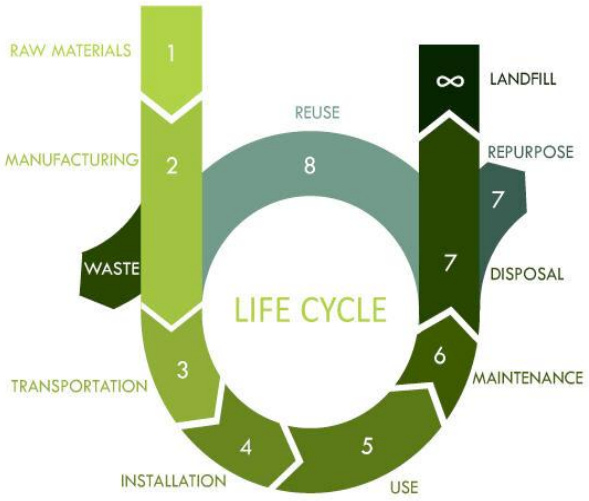

Figure 2.4 Stages of a Life Cycle)

ISO 14040 stipulates that there be four stages in the LCA framework, as shown in Figure 2.3: goal and scope definition, inventory analysis, impact assessment, and interpretation. Goal and scope unambiguously describe the product or process, as well as the "boundaries and environmental effects to be reviewed" (EPA 2006). The inventory analysis phase identifies and quantifies physical flows into and out of the boundaries of the product system. These flows include energy, water, and material inputs as well as emissions to the environment from processes within the system. Emissions shown here are in the form of "waste" as a result of manufacturing in Figure 2.4. Impact assessment allows the LCA practitioner to calculate environmental effects derived from of inventory

flows. The interpretation phase is used to constantly evaluate results in each phase, especially concerning uncertainty and assumptions made in the LCA process.

While LCA is helpful in assessing the potential environmental damage caused by a system, the proposed model is not a full LCA of toxic chemical use in industry. A full LCA would involve analysis of upstream processes, chemical transformation, transportation, infrastructure needs, and other activities associated with these chemicals. To perform such an analysis, boundary conditions, assumptions about resource use, and a more extensive economic model would need to be considered. The tool proposed here uses TRI as a subset of the US economy, more specifically, its manufacturing industry. While a full LCA and its many tools are useful for assessing many different product systems, this research borrows specific methods from the inventory analysis and impact assessment phases.

2.7.2 Life Cycle Impact Assessment

Impact assessment methodology uses the previously established inventory with its physical flows into and out of a system to assign quantifiable environmental impacts to flows out of the investigated system. In this study, the raw material contribution, manufacturing, transportation, and use of the listed chemicals are excluded, and instead, method of hazardous waste management is considered, whether it be release, recovery, or

treatment. Figure 2.5 shows the connection between the inventory and impact phases.

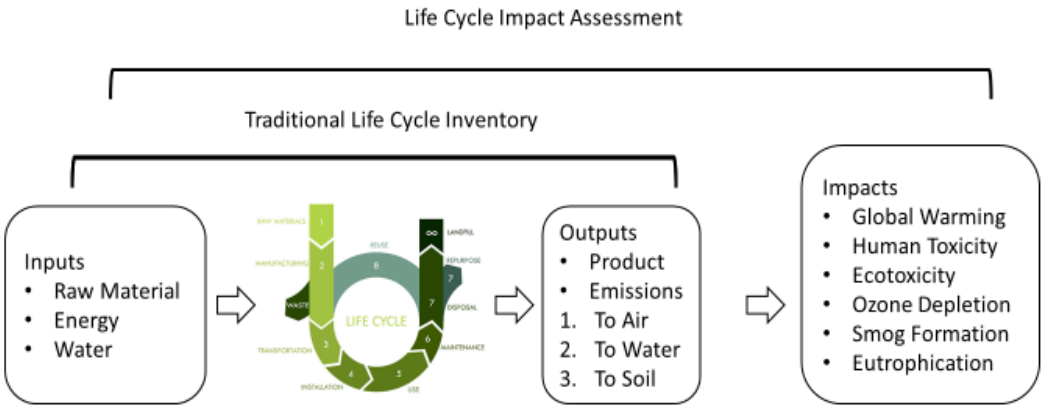

Figure 2.5 - Flow of Information in a Life Cycle Impact Assessment

TRI records the media of release to the environment, the most basic being release to air, water, and land. These chemicals have the potential to bring about certain environmental "midpoint" impacts such as global warming, human toxicity, and eutrophication. ***Midpoint impacts*** relate to physical measurables such as an increase in concentration of greenhouse gasses in the atmosphere, or the increased concentration of nitrogen, phosphorous, and potassium containing chemicals in the water that have been shown to cause algal blooms and consume dissolved oxygen. ***Endpoint impacts*** can be quantitative or semi-quantitative, but relate to broader environmental concerns, such as increased cancer rates among humans, or loss of biodiversity. The LCA practitioner leverages scientific data on chemicals and their impacts to assign appropriate impacts to specific chemicals.

Several models exist to evaluate environmental impacts based on chemical release. One such model is EPA's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI). The EPA developed TRACI as a tool for LCA practitioners to "minimize negative impacts while balancing environmental, economic, and social factors" when using the tool to assess chemicals in the environment (TRACI 2.0). TRACI operates by defining a single "equivalence unit" in each impact category. The equivalence unit is often a well-studied chemical known to contribute to an impact category, or some other unit of comparison. The equivalence unit is applied to individual chemicals and each chemical is assigned a "characterization factor" (CF), some multiple of the equivalence unit for comparison. For example, carbon dioxide is the equivalence unit for Global Warming Potential (GWP). Therefore, its CF is 1, or 1 kg-equivalent CO_2. Methane, however, has been found to be much more potent a greenhouse gas in the atmosphere and based on current estimates, absorbs at least 28 times more energy in the atmosphere that carbon dioxide over a 100 year period (IPPC 2007). Performing a simple calculation, 1 kg methane would have a GWP of 28 kg-eq CO_2, therefore the CF for methane in the GWP category is 28. This system extends to the other midpoint impacts discussed in this section including: human toxicity, ecotoxicity, eutrophication, acidification, and ozone depletion. Figure 2.6 from the International Reference Life Cycle Data System Handbook (2006) shows the progress of impact assessment from inventory results to midpoint and endpoint impacts.

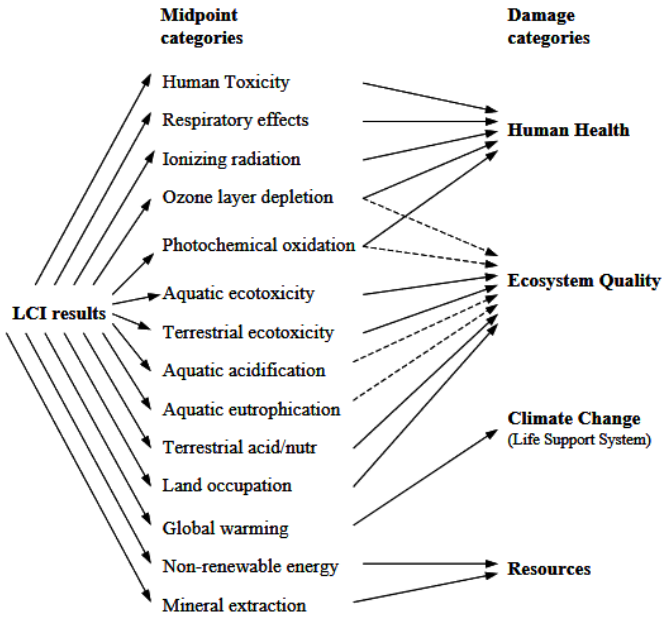

Figure 2.6 Impact categories and pathways covered by the IMPACT 2002+ methodology (ILCD Handbook, 2002)

2.7.3 Description of midpoint impact categories

Ozone Depletion Potential (ODP) is a measure of a chemical's potential to destroy stratospheric ozone (O_3). The ozone layer absorbs a large percentage of UV light from the sun's rays and prevents it from doing damage to humans and animals. Most ozone-depleting chemicals are chlorinated gasses, which when broken down in the upper atmosphere, release chlorine radicals that in turn break down ozone molecules.

Global Warming Potential (GWP) measures chemical contribution to global warming based on its potential to trap infrared radiation in the atmosphere. Global warming and

global climate change have the potential to negatively impact billions of lives in the form of extreme weather, drought, sea level rise, and a myriad of other pathways.

Eutrophication, or more accurately hyper-eutrophication, is the interaction between compounds, water, flora, and fauna in freshwater and marine systems. Certain compounds, mostly containing nitrogen and phosphorous, provide nutrients to organisms such as algae, which reproduce exponentially and consume dissolved oxygen in water, effectively suffocating other species in the same water body.

Smog Formation Potential measures a chemical's ability to produce smog, the result of the reaction between certain air pollutants and sunlight. Chemical mixtures and reactants can be hazardous to human health. The midpoint impact is the measured potential for a chemical to undergo some reaction to form a harmful constituent compound of smog.

Ecotoxicity is the hazard to "the constituents of ecosystems, animal (including human), vegetable and microbial, in an integral context" (Truhaut 1977). Here, ecotoxicity is used to evaluate trends in toxic releases to air, water, and land using a method that is repeatable and comparable between chemicals and industry.

2.7.4 TRI as a Subset of the US Economy

The TRI system captures only manufacturing industries handling hazardous chemicals and thus excludes various other industries. It does not include service industries nor facilities that handle hazardous materials, but do not meet threshold requirements. Additionally, TRI captures only US-based manufacturing facilities. With this geographic limitation, it does not account for chemical releases in other countries that

serve as US trade partners. Thus, this tool is limited to chemicals that are used strictly within the United States. While this work does not constitute a true LCA, which would seek to capture *upstream* releases associated with manufacturing raw materials that are imported to the US, it utilizes LCIA methods to inform decision making at the facility level.

Although it only captures a portion of the manufacturing industry, trends in the TRI dataset are good indicators of corresponding trends in the larger US economy; when the economy is doing well, manufacturing – and subsequently pollution – increases accordingly. For this reason, data results must be viewed from an economic vantage point, since the goal of any manufacturing facility is profitability and they are subject to changes in the economy. In such a system, reducing environmental damage from hazardous chemical release becomes extremely important. Reduction practices must combat increased consumption due to a growing population and economy.

2.8 Previous Work and Other Analyses

Previous work has investigated the TRI dataset and methods of analysis. Some have investigated toxicity weighting schemes to better understand chemical releases, while others have used geospatial mapping software to improve on EPA's data visualization. At this time, the EPA uses only its RSEI methodology to evaluate the TRI dataset, while non-governmental organizations (NGOs), university researchers, and state and local government may utilize other toxicity weighting schemes.

2.8.1 Toxicity Weight Analyses

Previous studies have been performed in order to address the weighting of toxic chemicals for analysis. Toffel and Marshall (2008) compared methods of evaluating chemical release inventories and several LCIA schemes, including TRACI, ecoindicator99, Indiana Relative Chemical Hazard Score (IRCHS), and Human Toxicity Potential (HTP). Overall, the authors analyzed 7 weighting methods based on their applicability to the TRI dataset. They recommend using the RSEI methodology to assess potential damage to human health and the TRACI methodology to investigate impacts on human health and the environment.

Lim et al. (2010) performed a priority screening of TRI chemicals using TRACI and RSEI methodologies to determine if the weighting methods highlight the same substances. The authors found that RSEI and TRACI did not agree based on their different evaluation methods and recommend that the two tools be used together to provide a more comprehensive result which incorporates both environmental and human health results.

Although multiple methods of weighting toxic chemical releases exist and have been analyzed by their potential to assess TRI data, there have not been visual data analyses using TRACI on the scale of this thesis.

2.8.2 Map-based Analyses

Gaona and Kohn (2016) of EPA outlined the use of "the visualization software Qlik for TRI data presentation and P2 outreach." Similarly to this thesis, the creators wanted to "study underlying patterns, find relationships, and understand data" among

other goals. Their tool focused on the food sector. Like other EPA analyses, Qlik tool was used to analyze chemical releases by mass only. However, their use of data visualization and mapping illustrates the utility of the mapping and data visualization tools.

3 METHODS

To produce a useful tool, large and complicated data sets needed to be combined in such a way that is convenient to the user, free and accessible, and scientifically rigorous. To that end, TRI data were combined with EPA's TRACI tool and North American Industry Classification System (NAICS) codes, and eventually compiled into Tableau workbooks, which can be published online for public viewing. The Tableau desktop visualization software is available via Clemson University licenses and provides relatively easy data manipulation, provided the data are prepared in the correct format. Additionally, a public version of the software is available online. The following section outlines the steps taken to retrieve and combine data in a platform conducive to public use.

3.1 TABLEAU

Tableau is a software package that allows users to easily upload and manipulate data, while creating bright and intuitive visualizations. It can connect to numerous data sources, including simple text files, Microsoft Excel, Microsoft Access, multiple SQL servers, Amazon Redshift, Google Analytics, and its own Tableau servers. The utility of the software is in its ability to communicate with multiple data sources, join them, and create a powerful interface for users interested in manipulating data. Additionally, and importantly for this tool, Tableau hosts an online gallery called Tableau Public, where users can upload their visualizations and data sets for others to view, utilize, and potentially improve. It serves as a virtual testing ground as well as a free public forum

where ideas can be shared.[1] The final product of this thesis will be uploaded to the online gallery, Tableau Public, at the time of its submission.

3.2 TRI DATA

Release data reported to EPA through Form R can be downloaded in separate yearly comma-separated value (CSV) format files through the EPA website, epa.gov.[2] Each year contains roughly 30,000 rows by 109 columns containing information on facility, location, TRI identification number, chemical handled, type of release, mass released, and other relevant data. These files were downloaded, and due to their cumbersome file size and format, split into separate databases for ease of use, and eventually recombined into a relational database using SQL. Important qualities of this data include use of Chemical Abstracts Service Registry Numbers (CAS Number) for simple chemical identification free from errors due to differences in spelling or nomenclature and the NAICS, a six-digit code used to identify to which industry a specific facility belongs. Using these numbering systems instead of a word-based identification system, it is possible to join separate data sources using these numbers as an identification key. This is an important quality when dealing with limited computing power but requiring information contained outside of the original database.

[1] Tableau Public workbooks can be found at https://public.tableau.com/en-us/s/gallery
[2] TRI basic data files can be downloaded at https://www.epa.gov/toxics-release-inventory-tri-program/tri-basic-data-files-calendar-years-1987-2016

3.3 TRACI

As mentioned above, TRACI relates individual compound releases to environmental damage. TRACI is incorporated as an impact assessment tool in many LCA software packages but in this case, the TRACI impact categories, along with their associated CFs for almost 4,000 individual chemicals were downloaded through the EPA website in a spreadsheet form (Bare 2011).[1] Column headings are impact categories, while each row contains a separate chemical, identified by both substance name and CAS Number. The body of the spreadsheet contains CFs for every listed chemical: zero if it does not contribute to a specific environmental impact and some non-zero factor if it is known to cause some harm in the respective impact category.

3.4 NAICS Codes and Descriptions

TRI data come complete with a general industry category, given by the first three numbers of the NAICS code, and a more specific industry subcategory given by the remaining three. Each facility can report up to six different NAICS codes that describe their type of manufacturing, but a vast majority of facilities report only one. The NAICS codes within the TRI database are then joined to an additional spreadsheet containing industry titles and subtitles.[2]

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[1] The TRACI spreadsheet can be downloaded at https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci

[2] The NAICS code sheet and descriptions can be found at https://www.census.gov/eos/www/naics/downloadables/downloadables.html

3.5 Data Integration

Facility, industry, chemical, and impact data were split and reorganized into a series of spreadsheets and databases. Specific data keys were maintained in each data location as shown in the entity relationship diagram Figure 3.1, shown below.

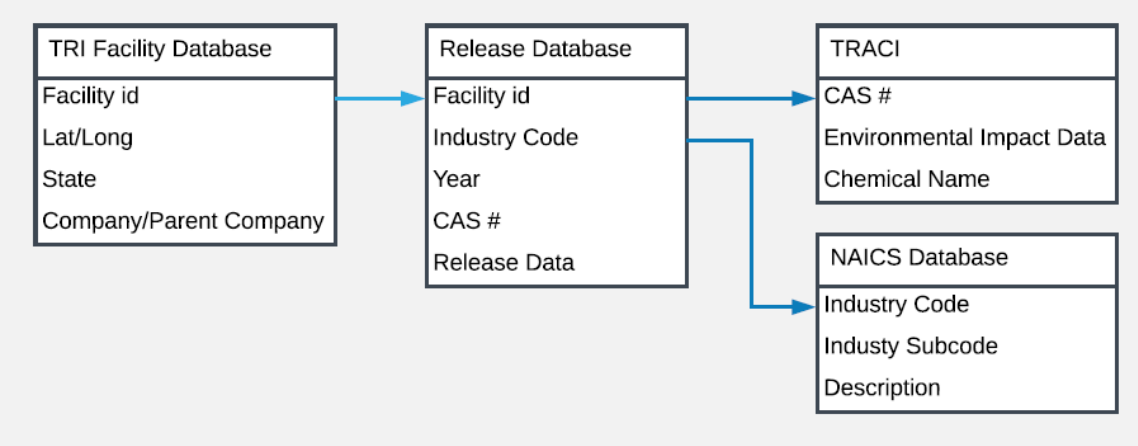


Figure 3.1 - Entity Relationship Diagram for TRI Data Management

Data keys make it easier to deal with large amounts of data, because they allow the user to maintain multiple, smaller, more manageable files while retaining the information contained in the relationships between the data. Thus, the facility information database contains only the TRI Facility ID number, geographic information, facility name, and the name of the parent company. It does not contain any chemical data. Conversely, the TRI database contains only Facility ID number, CAS Number, NAICS code, and mass release data. They are connected in Tableau by an "inner join" which connects the two data sources through their shared data key, the Facility ID number. The same approach is

taken with the TRACI data; it is linked only through the CAS Number which allows the user to make complex calculations in Tableau without dealing with matrix multiplication and enormous files.

3.6 Tableau Workbook Publication

The workbooks involved in this thesis are available on Tableau's public service. Follow the link https://public.tableau.com/profile/ted2836 or visit public.tableau.com/en-us/s and search "Ted Langlois". The visualizations available will allow the user to toggle through various subsets of TRI data, including the visualization used in the illustrative examples that follow. By making these datasets publicly available, we hope to increase the visibility of industry's role in pollution and inspire groups to take control of their air, water, and natural resources.

3.7 Improvements on Existing Tools

While there is no doubt that existing TRI data visualization tools from EPA are useful, they lack in certain areas including: availability of toxicity data, specific impact-related information, and utility of data visualization. EPA's work in data gathering and development of tools for analysis has been extremely important for public access to information, but now provides environmental data analysts the basis for a deeper understanding of hazardous chemical releases and their environmental effects.

3.7.1 Toxicity Data

The EPA National Analysis uses mass-based reporting to determine which chemicals are important to specific regions or industries. Figure 3.2 below shows the National Analysis results for the top five chemicals (by mass) released to air and water in South Carolina in calendar year 2016, while Figure 3.3 shows an ecotoxicity-based analysis of data from the same year.

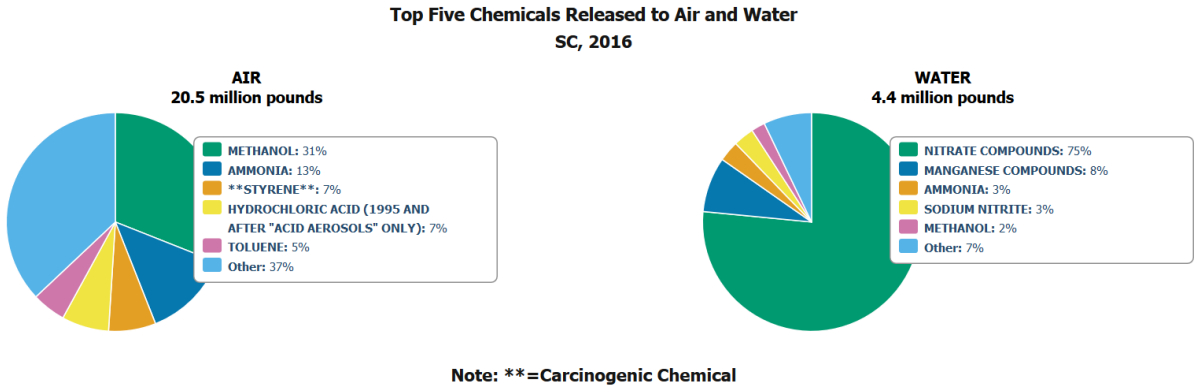


Figure 3.2 EPA National Analysis Fact Sheet, South Carolina 2016

Top Five Chemicals Released to Air and Water by Ecotoxicity SC, 2016

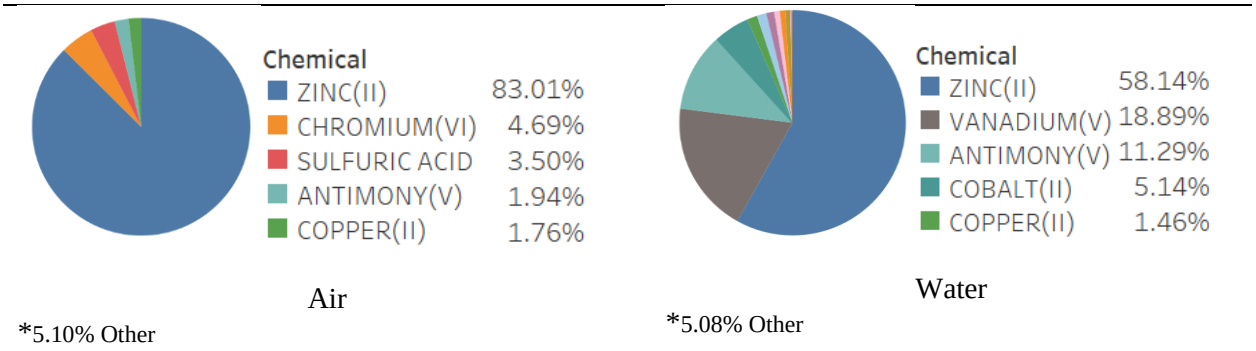


Figure 3.3 Tableau-Produced Ecotoxicity Analysis, South Carolina 2016

As is evident from the figures above, the National Analysis National Analysis gives the user only releases by mass without any context of potential for harm. Based on

this analysis, one would begin investigations into chemicals such as methanol and ammonia, which are commonly used in industry. An investigation based on TRACI characterization factors and impact categories leads to a different conclusion. In the TRACI method, ecotoxicty is measured in CTU_e – ecological comparative toxicity units – created to measure a chemical's impact to aquatic organisms (Rosenbaum et al. 2008) Through a comparison based on ecotoxicity, discussed in Appendix B, South Carolina conservationists and lawmakers should be overwhelmingly concerned with metal compounds containing zinc, and to a lesser extent, chromium, vanadium, and antimony. The tool created here outperforms mass-based TRI analysis by connecting chemical data to toxicity weighting schemes.

3.7.2 Impact-Based Data

TRACI improves the value of TRI data by defining the relationship between chemical releases and midpoint impacts. RSEI leverages toxicity weights and dose data to estimate risk to human health, but the method only aggregates risk from multiple chemical sources into a single risk score. It provides no deeper data insights into the types of environmental or human health damage may result in response to chemical exposure. While the RSEI method is scientifically sound and aggregated risk scoring is useful for comparison, it lacks the resolution required to analyze chemical releases for their specific effects.

The tool outlined here provides measurable midpoint impacts in the form of reference chemicals or toxicity units. Direct impact results can be traced back to their corresponding chemical and the contribution of specific facilities to various impact

categories can be analyzed on a chemical-to-chemical basis. This is a clear improvement on the EPA National Analysis in terms of toxicity and impact weighting and an improvement on RSEI in terms of understanding chemical effects rather than risk alone.

3.7.3 Data Visualization

Data mapping, trends, and visualizations are important for conveying environmentally relevant data. Both the National Analysis and RSEI tool have mapping components and the ability to generate charts based on chemical, location, industry, and in the case of RSEI, risk. Their interfaces are user friendly and easily accessible on the web. However, the user is limited to the design provided by the EPA on its web pages. For example, a user cannot view a side by side comparison of two states in the online tool. The integration of the TRI dataset with Tableau offers the user the unique opportunity to customize his or her data viewing experience. The user can download the dataset in question and re-create or modify workbooks published online. Additionally, Tableau provides features that allow the user to interact with graphs, charts, and maps, to sort and expand information in ways that the EPA-produced maps cannot.

4 RESULTS: ILLUSTRATIVE EXAMPLES AND DATA INSIGHTS

The results from this data analysis are presented as a set of illustrative examples and insights gleaned through data manipulation within the Tableau-based tool. The illustrative examples here serve a few specific purposes. They highlight the tool's potential to improve legislative and policy choices, identify specific compounds or industries that should be investigated as candidates for reduction activities, show potential data issues or accounting errors, and help industry, government, and communities prepare critical and vulnerable infrastructure in the event of natural disasters. The goal is to provide examples of successful use of the TRI data tool to show its ability to improve the usefulness of the TRI dataset.

4.1 ILLUSTRATIVE EXAMPLE 1: THE MONTREAL PROTOCOL

In 1987, the United States ratified the Montreal Protocol, in which 197 countries agreed to phase out the production and use of chemicals that destroy ozone in the stratosphere (Dept. of State 2016). These chemicals, which include chlorofluorocarbons (CFCs) rise into the stratosphere where they interact with sunlight and create free chlorine molecules which destroy ozone. (EPA "Basic Ozone Science" 2017). The destruction of the ozone layer results in more intense sunlight and increases the potential for the sun's rays to cause skin cancer.

When experts laid out the policy in 1987, it was expected to result in the "avoidance of more than 280 million cases of skin cancer, approximately 1.6 million skin cancer deaths, and more than 45 million cases of cataracts in the United States alone by the end of the century, with even greater benefits worldwide" (U.S. State Department 1987). The global agreement represents an impressive example of international cooperation and its positive effects. A NASA study published in early 2018 reported the first "direct proof" that the CFC ban has caused a reduction in stratospheric ozone depletion (NASA 2018). Using methods that measure directly the chemical composition of the ozone hole, researchers were able to determine not only that ozone depletion is decreasing, but that a lack of chlorine-containing chemicals is contributing.

Interestingly, CFCs are also extremely potent greenhouse gasses. They absorb photons and vibrate similarly to carbon dioxide and contribute to global warming yet have much greater potential to do so. The table below, from the Intergovernmental Panel on Climate Change (IPPC) fourth assessment report, shows the global warming potential of Montreal Protocol substance in units of kilograms carbon dioxide equivalent (IPPC 2007).

Table 4.1 Global Warming Potentials of Selected Greenhouse Gasses

Greenhouse Gas	Chemical Formula	GWP_{20} (kg CO_2-eq/kg)	GWP_{100} (kg CO_2-eq/kg)
Carbon dioxide	CO_2	1	1
Methane	CH_4	84	28
Nitrous Oxide	N_2O	264	265
Carbon Tetrachloride	CCl_4	2700	1400
CFC-11 (Freon-11)	CCl_3F	6730	4750
CFC-12	CCl_2F_2	11000	10900
CFC-13	$CClF_3$	10800	14400

IPPC 4th Assessment, 2007

4.1.1 Ozone Depletion Potential Decrease

Figure 4.1 shows the reduction in ozone depletion, measured in units of ODP, equal to the kilogram equivalent of the reference chemical, CFC-11. In the late 1980s and early 1990s, soon after the Montreal Protocol took effect, a significant decrease in the production-related release of ozone depleting chemicals occurred as evidenced below. As a response to the phasing out of other CFCs, the use of CFC-12 and methyl bromide spiked shortly after 1991 as they were used briefly in place of banned CFCs.

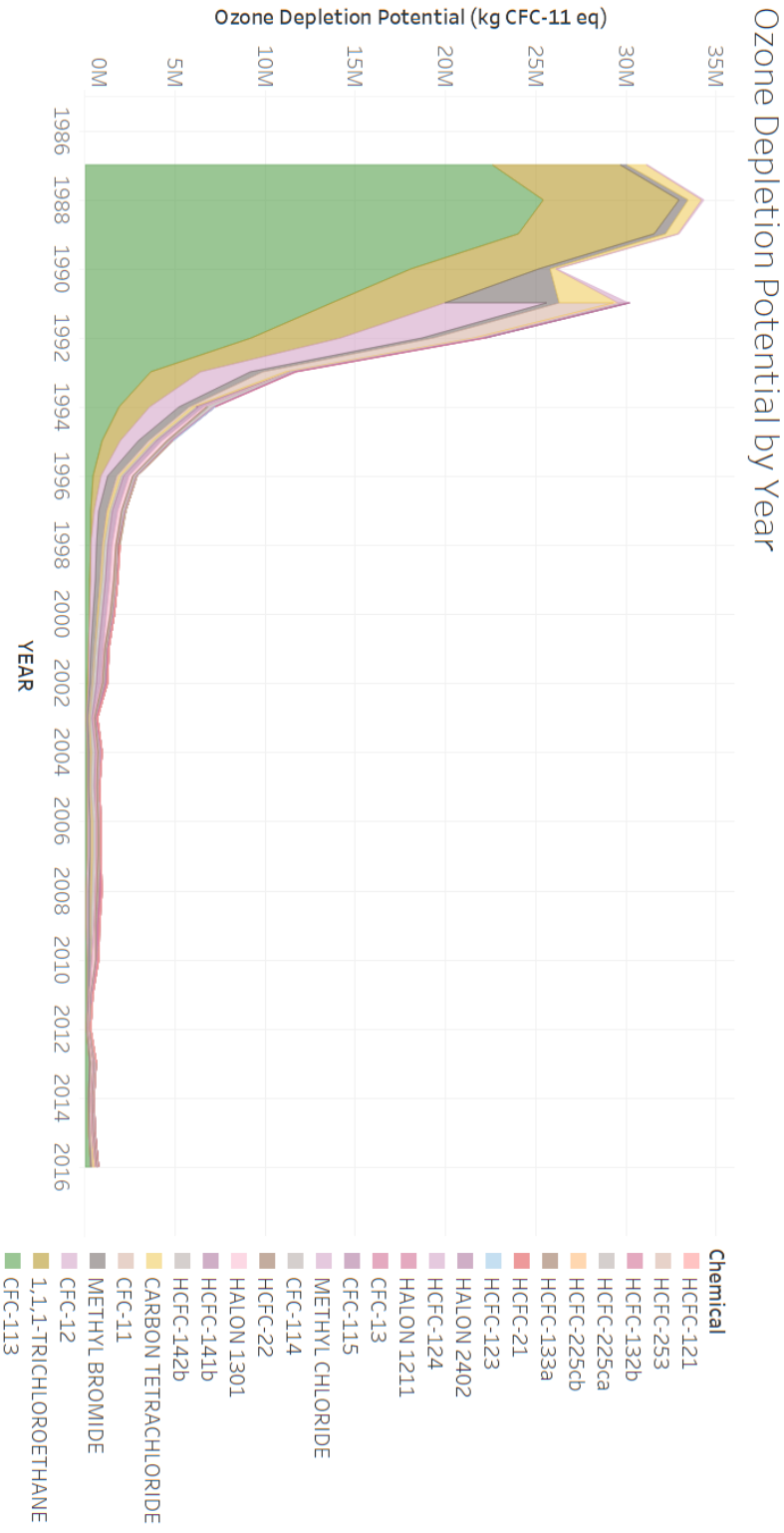


Figure 4.1 Ozone Depleting TRI Chemicals 1986-2016

It is encouraging, from an environmental and human health viewpoint, that a science-backed policy was suggested, implemented, and found to be successful.

4.1.2 Global Warming Potential Decrease

It is clear from Figure 4.1 that CFCs are extremely potent ozone depletors. In addition to this quality, they are also potent greenhouse gasses. Although CFCs' potential to accelerate global warming and global climate change weren't the reasons behind the protocol, their management by the Montreal Protocol helps curtail their contribution. Figure 4.2 shows similar reductions in GWP achieved after the Montreal rules were implemented, with minor differences.

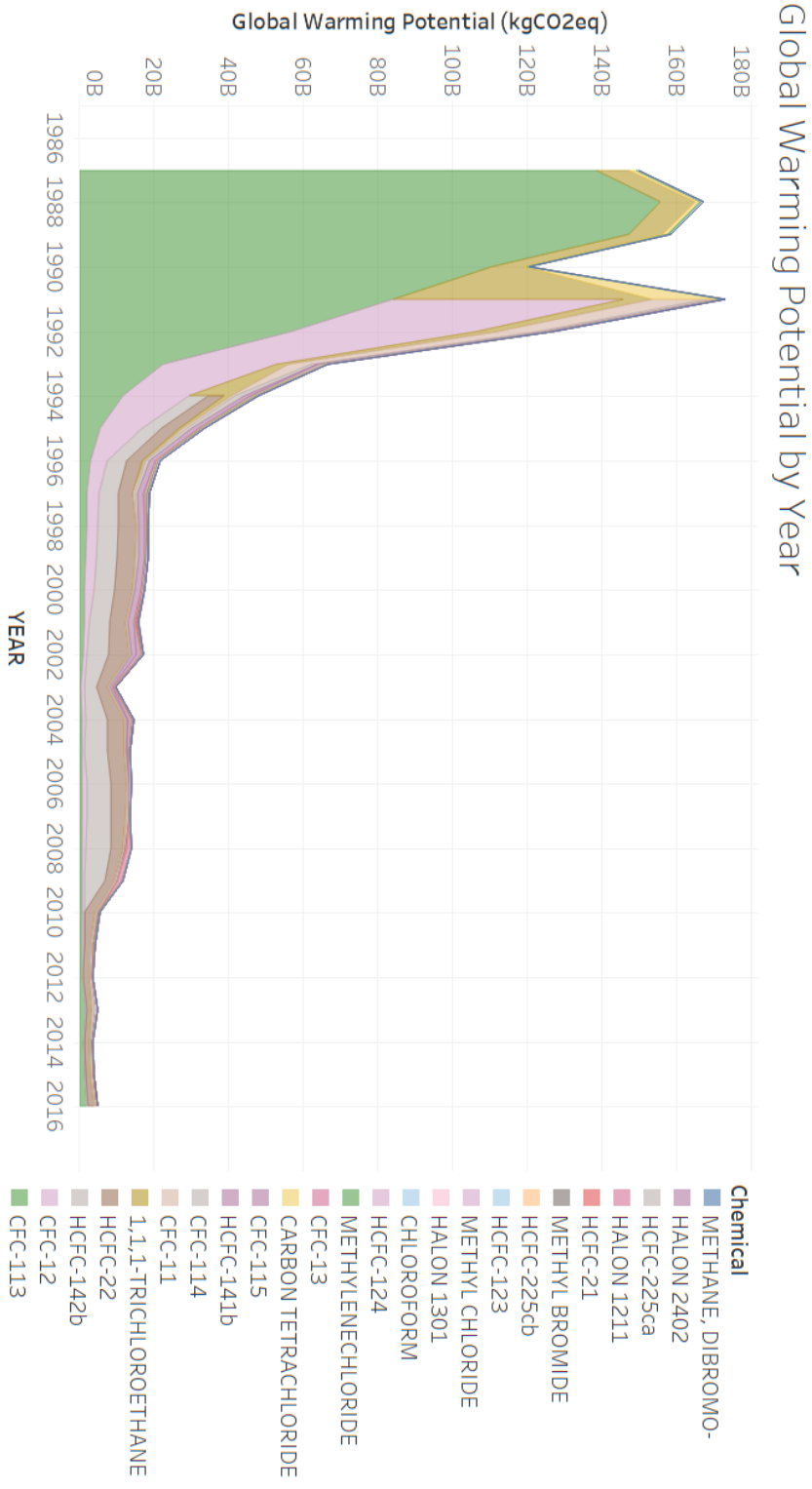
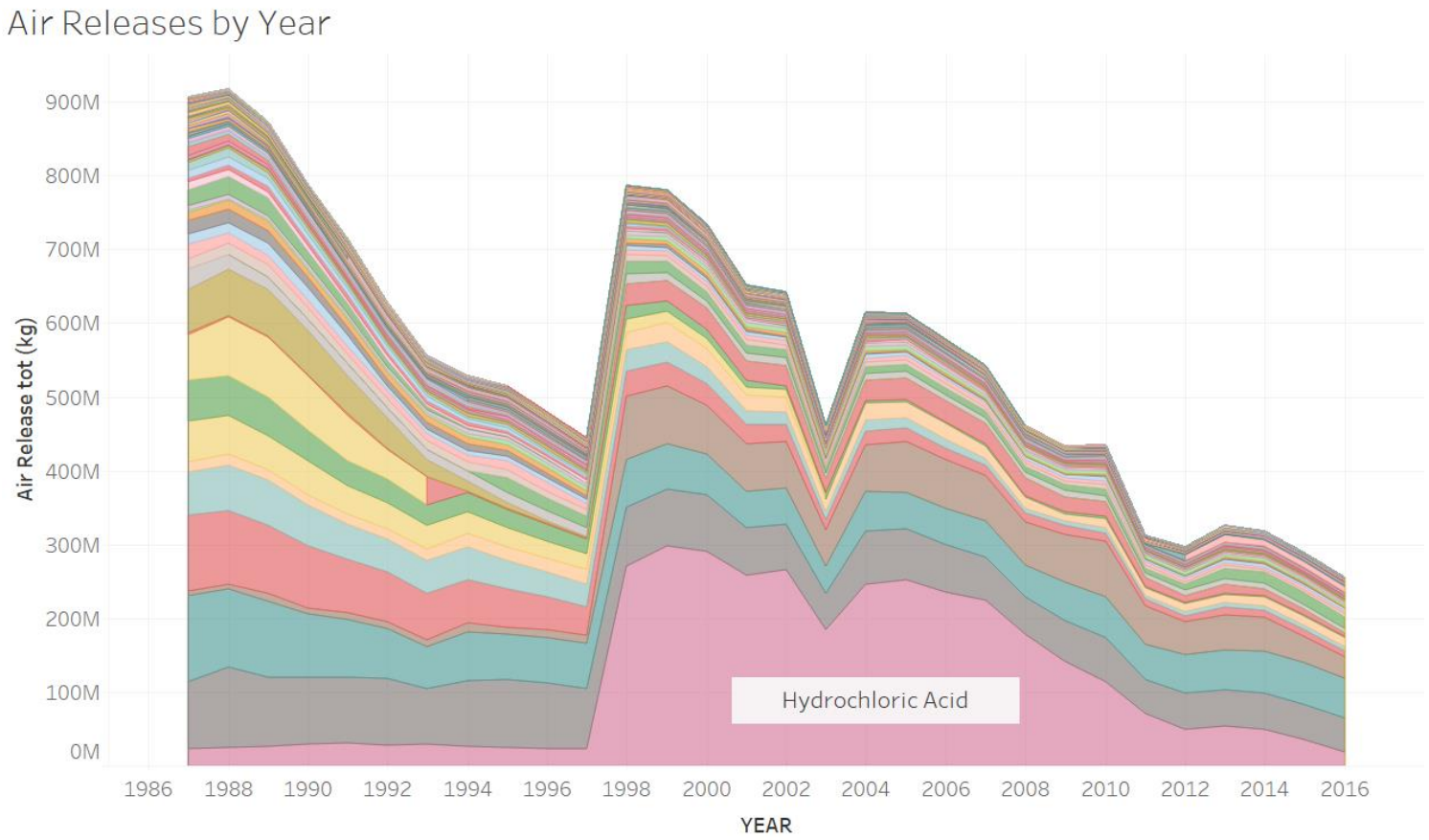


Figure 4.2 TRI Greenhouse Gasses 1986-2016

It is interesting to note the differences in a chemical's contribution to different midpoint categories. CFC-12, for example, was added to the TRI list in 1991 and contributes more to total global warming potential than it does to total ozone depletion potential. The figure also highlights an important issue with the data involved in this analysis. Due to the addition of CFC-12 in 1991, it appears that GWP increases briefly in the year following. However, it is reasonable to assume that CFC-12 was being produced and subsequently released in the United States prior to 1991 and in larger quantities. Assuming this is true, it appears that GWP, and by extension ODP, decreased steadily beginning in the late 1980s as a direct result of the Montreal Protocol.

4.2 Illustrative Example 2: Hydrogen Chloride air releases from electric power generation

In identifying midpoint trends, it is useful to view air release trends more broadly. Since the Montreal Protocol was effective in reducing ozone depleting chemicals, it may be representative of broader trends in emissions reduction pursuant to the goal of the TRI. Figure 4.3 includes all releases to air over time, with chemicals sorted by color and mass released. While there is a general downward trend, there is a considerable increase after 1997 due to a large increase in reported emissions of hydrochloric acid.



The plot of sum of Air Release tot (kg) for YEAR. Color shows details about Chemical. The view is filtered on Chemical, which keeps 473 of 495 members.

Figure 4.3 Total Air Releases 1986-2016

Excluding hydrochloric acid data, air releases continue their trend of reduction relatively uninterrupted in Figure 4.4 below.

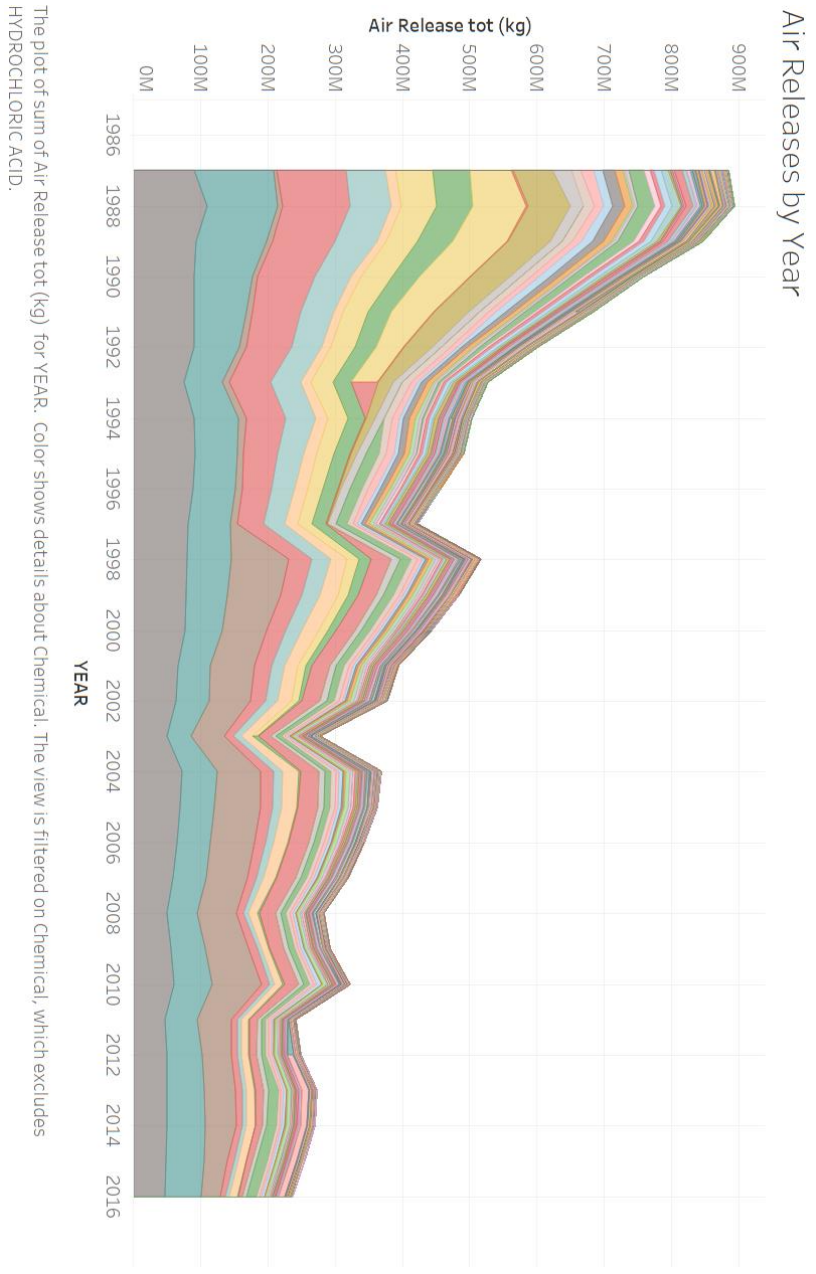


Figure 4.4 Non-HCl Air Releases 1986-2016

This apparent data anomaly introduces the question: what changed in 1997 to include hundreds of millions of kilograms of HCl that were not reported previously? According to the official EPA registry of TRI chemicals, HCl has always been included in aerosol form. Thus, there was no change in *chemical* reporting that could explain the sudden increase in HCl after 1997. Figure 4.5 shows HCl air releases over time with colors representing industry categories.

Figure 4.5 Recorded HCl Emissions 1986-2016

The figure shows that almost all the HCl reported after 1997 can be attributed to a single industry sector: Electric Power Generation, Transmission and Distribution. This industry did not appear in the data before the year in question. For the reporting year 1998, and each year after, the EPA required power plants that burn coal or oil to report their chemical uses to TRI, based on a projection that suggested that "the magnitude of electric utility industry releases will surpass those of the manufacturing industries which currently report to TRI" (Rubin, 1999). Thus, emissions data for HCl, which was previously unreported from the power generation industry suddenly appears in the record.

The addition of an industry sector and its effect on emissions data is problematic. In some ways it is analogous to finding a ten-dollar bill in one's pocket. One is glad to have the money, but one also must recognize that he or she must have lost ten dollars at some point. Differences in reporting methods and requirements lead to important questions. If all industries are not required to report their emissions, is there much point to tracking them? Can we earnestly tout our chemical use reductions without a complete set of data? While the data is disappointingly incomplete prior to 1998, the data since then is quite illuminating.

HCl emissions peak in the late 1990s and early 2000s, as evidenced by Figure 4.5. However, there is a roughly one-third reduction in total releases between 1999 and 2003, followed by another increase before more serious reductions begin to occur around 2007. These reductions were a direct result of changes in federal legislation. As a Hazardous Air Pollutant (HAP), HCl is regulated by National Emission Standards for Hazardous Air Pollutants (NESHAP). This standard sets limits for "production facilities" that are a

major source of a specific HAP. In 2001, a rule change was proposed to limit the release of HCl from industrial facilities (Federal Register 2001). In response to the proposal, it appears that industrial facilities preemptively began to reduce HCl, leading to a local minimum in 2003. Despite this new rule, HCl releases rebounded until 2006 when, after public comment, the EPA finalized further amendments to NESHA, and required facilities with "major sources to meet HAP emission standards and implement work practice standards that reflect the application of maximum achievable control technology" and included clarifications on "applicability provisions, emissions standards, and testing" (National Register). Again, despite a lack of early data, the hydrochloric acid rule seems to be another example of positive outcomes from both the availability of toxic release data and government intervention for the purposes of safeguarding human health.

4.3 Illustrative Example 3: Natural Disaster Planning and Resilience in the Aftermath of Hurricane Harvey

In late August of 2017, Category 4 hurricane Harvey made landfall on the Gulf Coast of Texas (CNN 2017). The storm broke the United States record for rainfall from a single storm and flooded much of the southeastern part of the state. A unique combination of geographic, economic, and meteorological factors contributed to the severity of the flooding and its potential effects on the environment and human health. First, Houston, America's fourth largest city, has grown 23% in population since 2001

and its metropolitan area measures 9,000 square miles. Urban sprawl has resulted in the construction of more impermeable surfaces such as paved streets, parking lots, and sidewalks, which reduces an area's ability to absorb water and increases the severity of flooding events.

Second, the low-lying city is home to numerous petroleum companies, refineries, and chemical manufacturers. These chemical consumers and producers contribute significantly to the TRI under normal operation. During natural disaster events, they become infrastructure critical to keep intact. The accidental release of many of the chemicals stored and used in these facilities could cause major damage to ecosystems and human health.

In some areas, the 500-year flood event caused extensive damage, impacting both TRI facilities as well as homes (Hubbard 2017). A 2017 New York Times article reported that over 40 facilities released toxic chemicals in the aftermath of the hurricane (Griggs et al. 2017). In order to prepare for cleanup and investigate the types of compounds and their potential environmental impacts, an analysis of these locations was performed. ArcGIS was used to identify any facility within 1000 feet of the observed flood extent. These facilities were then selected in Tableau and designated at risk for flooding. The 1000-foot buffer was chosen to account for reported facility coordinates that reflect a street address rather than the center of the facility itself. Figure 4.6 below reflects the location of TRI facilities within the flood zone as well as the flood extent.

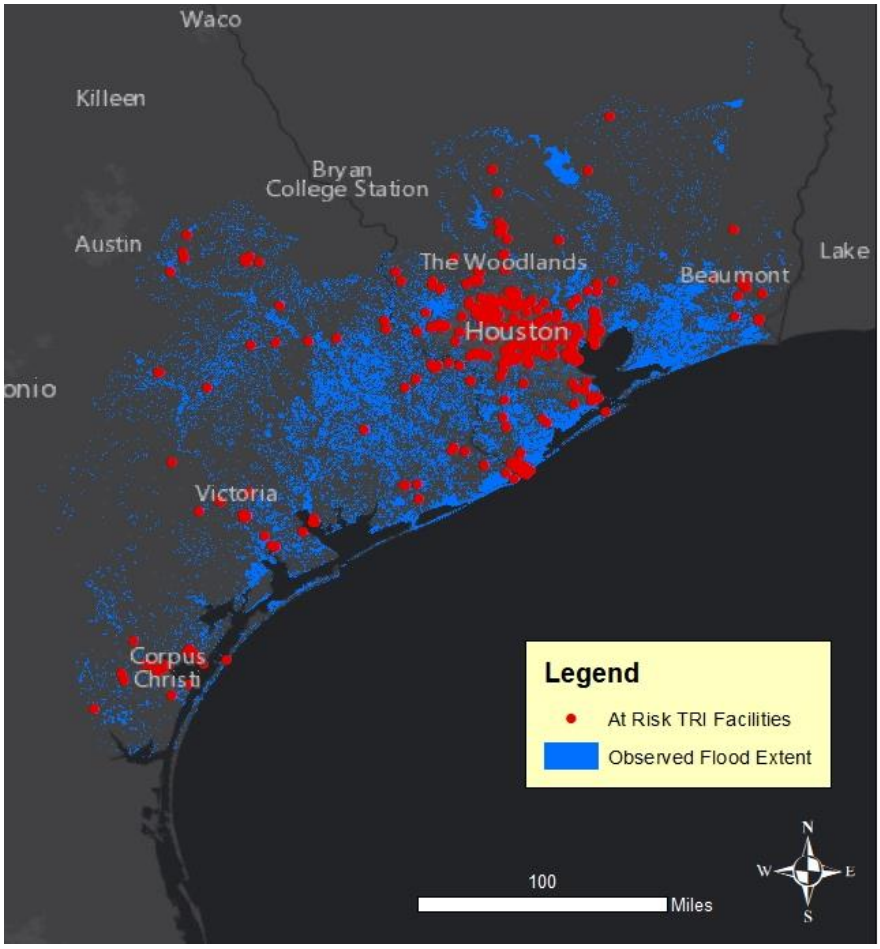


Figure 4.6 Map of Observed Flood Extent with TRI Facilities

To prepare for a flood event such as Harvey or to predict what classes of chemicals may be present in soil and groundwater after release, it is important to create an inventory of chemicals present in vulnerable facilities. The Tableau tool can be used to assess types of chemical and their potential ecotoxicity effects in water. Figure 4.7 shows the top 10 chemical processors in the affected area by mass reported to TRI. It is useful to note that the data available is the total mass of compound "released" in some capacity during calendar year 2016. Here, "total releases" refer to any chemical processed according to

the P2 hierarchy: energy recover, recycling, treatment, and release to the environment. At any given time, the chemicals presented in this figure are certainly not present in their respective facilities, but it can be reasonably assumed that some fraction of each of them is present at a given moment. Additionally, without access to the 2017 data, an accurate sum of specific compounds cannot be provided, 2016 data must be used as a surrogate.

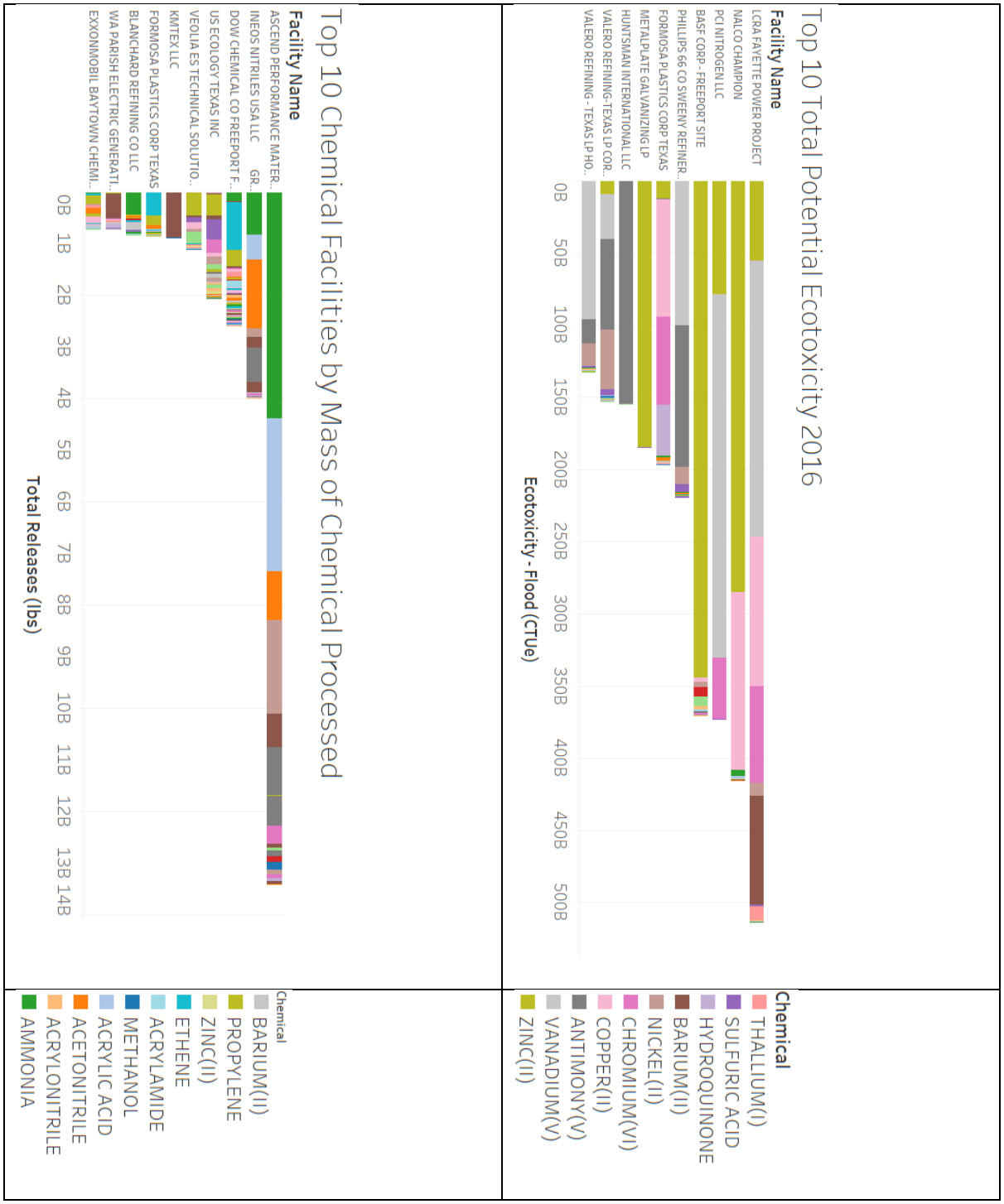


Figure 4.7 Chemical Inventory for Potentially Flooded Texas TRI Facilities – Top 10 by Mass

Figure 4.8 Chemical Inventory for Potentially Flooded Texas TRI Facilities – Top 10 by Ecotoxicity

The chemicals present in these ten facilities are commonly consumed in large quantities by chemical manufacturers. They appear in the TRI National Analysis in large quantities. However, while it is useful to understand which chemicals are used in Texas facilities and in what amount, the compounds present here may not be the most toxic chemicals present in the Gulf Coast region. Figure 4.8 lists the top 10 facilities based on potential to cause ecosystem damage in a major flood event. The unit for ecotoxicity applied through TRACI is CTU_e, which is proportional to the potentially affected fraction of species in an ecosystem (Rosenbaum 2008). It is important to note here that to cause the damage mentioned, the facility would have to become completely flooded and lose a complete years' worth of chemical inventory. Still, it is useful to understand potential hazards associated with natural disaster events.

By mass, none of the top 10 chemical processors have the potential to be the top 10 sources of ecotoxicity in a flood event. This shows the role toxicity plays in assessing potential environmental damage, and the usefulness of an LCIA tool to weight chemicals based on their impacts. Disaster awareness and planning based on mass would severely undervalue the facilities that could be a greater risk to human and environmental health in the event of an incident.

5 Conclusions and Future Work

5.1 A Tool for Industry, Government, and Communities

The online tool produced by this thesis is meant to show the potential for data visualization tools like Tableau, combined with toxicity weighting schemes, to improve our understanding of toxic releases and their sources. In the age of big data and real-time analytics, more possibilities exist for improvement and decision-making built around the protection of human health and the environment. The thought behind the TRI program when it was announced in 1986 was to create unprecedented public access to data that was previously unreachable. Today, we have even greater access and more powerful tools to analyze that data.

5.2 A Model for Better Data Analysis

As a visualization tool, Tableau is incredibly useful and intuitive. It is not the only tool available for data analysts, and perhaps not even the most powerful. However, the model presented here – data collection, compilation, combination with an outside scientific methodology – can be repeated with a great number of disparate data sets. For example, the same methods could be applied to an analysis of the National Emissions Inventory, a separate, EPA-produced set of environmental data, or with Canada's National Pollution Release Inventory. Coal and natural gas fired power plants monitoring NO_x, SO_x, mercury, and particulate matter could report in real time to a data-

gathering system. Repeating the process shown above, the public could receive real-time information on the environmental and health hazards that power plant emissions cause.

As mentioned in section 2.8, other impact assessment and toxicity weighting tools exist. The author would recommend that future work expand the use of the TRACI tool to include other LCIA packages such as ecoindicator99 (2000) or ReCiPe (2016). The integration of these methodologies with TRACI and the Tableau-based tool could confirm or challenge the results of this thesis and lead to more nuanced and rich understandings of the TRI dataset.

On the subject of repeating or improving on this research, the author recommends that future TRI dataset users download EPA's yearly .csv files and import them directly into an SQL database rather than combining the files first in another format. Additionally, it would be useful for EPA to provide the raw data in a long data format, in a single database, directly to users. This would effectively remove the necessity of downloading each year's data individually and allow data analysis to begin without much work by the end user.

However it is used, we have access to more environmentally relevant information than at any point in history. The responsibility is on us to use data to protect our resources and the quality of our environment.

APPENDIX A

A1 - TRI Form A

(IMPORTANT: Read instructions before completing form; type or use fill-and-print form) Form Approved OMB Number: 2025-0009 Approval Expires: 07/31/2014 **Page 1 of ___**

EPA United States Environmental Protection Agency

TOXICS RELEASE INVENTORY FORM A

WHERE TO SEND COMPLETED FORMS: 1. TRI Data Processing Center P. O. Box 10163 Fairfax, VA 22038	2. APPROPRIATE STATE OFFICE OR (See instructions in Appendix E)	TRI Facility ID Number

This section only applies if you are revising or withdrawing a previously submitted form, otherwise leave blank.	**Revision (Enter up to two code(s))**		**Withdrawal (Enter up to two code(s))**	

IMPORTANT: See instructions to determine when "Not Applicable (NA)" boxes should be checked.

PART I. FACILITY IDENTIFICATION INFORMATION

SECTION 1. REPORTING YEAR _____

SECTION 2. TRADE SECRET INFORMATION

2.1	Are you claiming the toxic chemical identified on page 2 as a trade secret? ☐ Yes (Answer question 2.2; attach substantiation forms) ☐ No (Do not answer 2.2; go to Section 3)	2.2	Is this copy ☐ Sanitized ☐ Unsanitized (Answer only if "Yes" in 2.1)

SECTION 3. CERTIFICATION **(Important: Read and sign after completing all form sections.)**

I hereby certify that to the best of my knowledge and belief, for each toxic chemical listed in this statement, the annual reportable amount as defined in 40 CFR 372.27(a), did not exceed 500 pounds for this reporting year and that the chemical was manufactured, processed, or otherwise used in an amount not exceeding 1 million pounds during this reporting year.

Name and official title of owner/operator or senior management official:	Signature:	Date signed:

SECTION 4. FACILITY IDENTIFICATION

4.1	Facility or Establishment Name	TRI Facility ID Number	
	Physical Street Address	Mailing Address (if different from physical street address)	
	City/County/State/ZIP Code	City/State/ZIP Code	Country (Non-US)
4.2	This report contains information for: (Important: Check c or d if applicable)	c. ☐ A Federal facility	d. ☐ GOCO
4.3	Technical Contact Name		Telephone Number (include area code)
	Email Address		
4.4	Public Contact Name		Telephone Number (include area code)
	Email Address		

4.5	NAICS Code(s) (6 digits)	Primary a.	b.	c.	d.	e.	f.
4.6	Dun & Bradstreet Number(s) (9 digits)	a.					
		b.					

SECTION 5. PARENT COMPANY INFORMATION

5.1	Name of U.S. Parent Company (for TRI Reporting purposes)	No U.S. Parent Company (for TRI Reporting purposes) ☐	
5.2	Parent Company's Dun & Bradstreet Number	NA ☐	

EPA Form 9350 -2 (Rev. 07/2011) - Previous editions are obsolete.

- - - - -

(IMPORTANT: Read instructions before completing form; type or use fill-and-print form)

Form Approved OMB Number: 2025-0009
Approval Expires: 07/31/2014

EPA FORM A
PART II. CHEMICAL IDENTIFICATION

Do not use this form for reporting PBT chemicals, including Dioxin and Dioxin-like Compounds*

TRI Facility ID Number

SECTION 1. TOXIC CHEMICAL IDENTITY	**Report ___ of ___**
1.1	CAS Number (Important: Enter only one number exactly as it appears on the Section 313 list. Enter category code if reporting a chemical category.)
1.2	Toxic Chemical or Chemical Category Name (Important: Enter only one name exactly as it appears on the Section 313 list.)
1.3	Generic Chemical Name (Important: Complete only if Part 1, Section 2.1 is checked "Yes". Generic Name must be structurally descriptive.)
SECTION 2. MIXTURE COMPONENT IDENTITY (Important: DO NOT complete this section if you completed Section 1 above)	
2.1	Generic Chemical Name Provided by Supplier (Important: Maximum of 70 characters, including numbers, letters, spaces, and punctuation.)
SECTION 1. TOXIC CHEMICAL IDENTITY	**Report ___ of ___**
1.1	CAS Number (Important: Enter only one number exactly as it appears on the Section 313 list. Enter category code if reporting a chemical category.)
1.2	Toxic Chemical or Chemical Category Name (Important: Enter only one name exactly as it appears on the Section 313 list.)
1.3	Generic Chemical Name (Important: Complete only if Part 1, Section 2.1 is checked "Yes". Generic Name must be structurally descriptive.)
SECTION 2. MIXTURE COMPONENT IDENTITY (Important: DO NOT complete this section if you completed Section 1 above)	
2.1	Generic Chemical Name Provided by Supplier (Important: Maximum of 70 characters, including numbers, letters, spaces, and punctuation.)
SECTION 1. TOXIC CHEMICAL IDENTITY	**Report ___ of ___**
1.1	CAS Number (Important: Enter only one number exactly as it appears on the Section 313 list. Enter category code if reporting a chemical category.)
1.2	Toxic Chemical or Chemical Category Name (Important: Enter only one name exactly as it appears on the Section 313 list.)
1.3	Generic Chemical Name (Important: Complete only if Part 1, Section 2.1 is checked "Yes". Generic Name must be structurally descriptive.)
SECTION 2. MIXTURE COMPONENT IDENTITY (Important: DO NOT complete this section if you completed Section 1 above)	
2.1	Generic Chemical Name Provided by Supplier (Important: Maximum of 70 characters, including numbers, letters, spaces, and punctuation.)
SECTION 1. TOXIC CHEMICAL IDENTITY	**Report ___ of ___**
1.1	CAS Number (Important: Enter only one number exactly as it appears on the Section 313 list. Enter category code if reporting a chemical category.)
1.2	Toxic Chemical or Chemical Category Name (Important: Enter only one name exactly as it appears on the Section 313 list.)
1.3	Generic Chemical Name (Important: Complete only if Part 1, Section 2.1 is checked "Yes". Generic Name must be structurally descriptive.)
SECTION 2. MIXTURE COMPONENT IDENTITY (Important: DO NOT complete this section if you completed Section 1 above)	
2.1	Generic Chemical Name Provided by Supplier (Important: Maximum of 70 characters, including numbers, letters, spaces, and punctuation.)

*See the TRI Reporting Forms and Instructions manual for the list of PBT Chemicals (including Dioxin and Dioxin-like Compounds)

A2 – TRI Form R

(IMPORTANT: Read instructions before completing form; type or use fill-and-print form)

Form Approved OMB Number: 2025-0009
Approval Expires: 07/31/2014

EPA
United States
Environmental Protection Agency

FORM R

Section 313 of the Emergency Planning and Community Right-to-Know Act of 1986, also Known as Title III of the Superfund Amendments and Reauthorization Act

TRI Facility ID Number

Toxic Chemical, Category, or Generic Name

WHERE TO SEND COMPLETED FORMS: 1. TRI Data Processing Center, P. O. Box 10163, Fairfax, VA 22038 2. APPROPRIATE STATE OFFICE (See instructions in Appendix E)

This section only applies if you are revising or withdrawing a previously submitted form, otherwise leave blank.

Revision (Enter up to two code(s)) ☐ ☐

Withdrawal (Enter up to two code(s)) ☐ ☐

IMPORTANT: See instructions to determine when "Not Applicable (NA)" boxes should be checked.

PART I. FACILITY IDENTIFICATION INFORMATION

SECTION 1. REPORTING YEAR _____

SECTION 2. TRADE SECRET INFORMATION

2.1 Are you claiming the toxic chemical identified on page 2 as a trade secret?
☐ Yes (Answer question 2.2; attach substantiation forms) ☐ No (Do not answer 2.2; go to Section 3)

2.2 Is this copy ☐ Sanitized ☐ Unsanitized (Answer only if "Yes" in 2.1)

SECTION 3. CERTIFICATION (Important: Read and sign after completing all form sections.)

I hereby certify that I have reviewed the attached documents and that, to the best of my knowledge and belief, the submitted information is true and complete and that the amounts and values in this report are accurate based on reasonable estimates using data available to the preparers of this report.

Name and official title of owner/operator or senior management official:	Signature:	Date signed:

SECTION 4. FACILITY IDENTIFICATION

4.1	Facility or Establishment Name	TRI Facility ID Number	
	Physical Street Address	Mailing Address (if different from physical street address)	
	City/County/State/ZIP Code	City/State/ZIP Code	Country (Non-US)
4.2	This report contains information for: (Important: Check a or b; check c or d if applicable)	a. ☐ An entire facility b. ☐ Part of a facility c. ☐ A federal facility d. ☐ GOCO	
4.3	Technical Contact Name		Telephone Number (include area code)
	Email Address		
4.4	Public Contact Name		Telephone Number (include area code)
	Email Address		
4.5	NAICS Code(s) (6 digits)	Primary a. / b. / c. / d. / e. / f.	
4.6	Dun & Bradstreet Number(s) (9 digits)	a. / b.	

SECTION 5. Parent Company Information

5.1	Name of U.S. Parent Company (for TRI Reporting purposes)	No U.S. Parent Company (for TRI Reporting purposes) ☐	
5.2	Parent Company's Dun & Bradstreet Number	NA ☐	

EPA form 9350 -1 (Rev. 07/2011) – Previous editions are obsolete.

(IMPORTANT: Read instructions before completing form; type or use fill-and-print form)

Form Approved OMB Number: 2025-0009
Approval Expires: 07/31/2014

FORM R

Part II. CHEMICAL-SPECIFIC INFORMATION

TRI Facility ID Number
Toxic Chemical, Category, or Generic Name

SECTION 1. TOXIC CHEMICAL IDENTITY

(Important: DO NOT complete this section if you are reporting a mixture component in Section 2 below.)

1.1	CAS Number (Important: Enter only one number exactly as it appears on the Section 313 list. Enter category code if reporting a chemical category.)
1.2	Toxic Chemical or Chemical Category Name (Important: Enter only one name exactly as it appears on the Section 313 list.)
1.3	Generic Chemical Name (Important: Complete only if Part I, Section 2.1 is checked "Yes". Generic Name must be structurally descriptive.)

SECTION 2. MIXTURE COMPONENT IDENTITY

(Important: DO NOT complete this section if you completed Section 1.)

2.1	Generic Chemical Name Provided by Supplier (Important: Maximum of 70 characters, including numbers, letters, spaces, and punctuation.)

SECTION 3. ACTIVITIES AND USES OF THE TOXIC CHEMICAL AT THE FACILITY

(Important: Check all that apply.)

3.1 Manufacture the toxic chemical:	3.2 Process the toxic chemical:	3.3 Otherwise use the toxic chemical:
a. ☐ Produce b. ☐ Import If Produce or Import c. ☐ For on-site use/processing d. ☐ For sale/distribution e. ☐ As a byproduct f. ☐ As an impurity	a. ☐ As a reactant b. ☐ As a formulation component c. ☐ As an article component d. ☐ Repackaging e. ☐ As an impurity	a. ☐ As a chemical processing aid b. ☐ As a manufacturing aid c. ☐ Ancillary or other use

SECTION 4. MAXIMUM AMOUNT OF THE TOXIC CHEMICAL ON-SITE AT ANY TIME DURING THE CALENDAR YEAR

4.1	☐ (Enter two digit code from instruction package.)	

SECTION 5. QUANTITY OF THE TOXIC CHEMICAL ENTERING EACH ENVIRONMENTAL MEDIUM ON-SITE

			A. Total Release (pounds/year*) (Enter a range code** or estimate)	B. Basis of Estimate (Enter code)	C. Percent from Stormwater
5.1	Fugitive or non-point air emissions	NA ☐			
5.2	Stack or point air emissions	NA ☐			
5.3	Discharges to receiving streams or water bodies (Enter one name per box)	NA ☐			
	Stream or Water Body Name				
5.3.1					
5.3.2					
5.3.3					

If additional pages of Part II, Section 5.3 are attached, indicate the total number of pages in this box ☐ and indicate the Part II, Section 5.3 page number in this box. ☐ (Example: 1, 2, 3, etc.)

*For Dioxin or Dioxin-like compounds, report in grams/year.
**Range Codes: A= 1-10 pounds; B= 11-499 pounds; C= 500-999 pounds.

(IMPORTANT: Read instructions before completing form; type or use fill-and-print form)

Form Approved OMB Number: 2025-0009
Approval Expires: 07/31/2014

FORM R

Part II. CHEMICAL-SPECIFIC INFORMATION (CONTINUED)

TRI Facility ID Number
Toxic Chemical, Category, or Generic Name

SECTION 5. QUANTITY OF THE TOXIC CHEMICAL ENTERING EACH ENVIRONMENTAL MEDIUM ON-SITE (continued)

		NA	A. Total Release (pounds/year*) (Enter a range code** or estimate)	B. Basis of Estimate (Enter code)
5.4.1	Underground Injection on-site to Class I Wells	☐		
5.4.2	Underground Injection on-site to Class II-V Wells	☐		
5.5	Disposal to land on-site			
5.5.1A	RCRA Subtitle C landfills	☐		
5.5.1B	Other landfills	☐		
5.5.2	Land treatment/application farming	☐		
5.5.3A	RCRA Subtitle C surface impoundments	☐		
5.5.3B	Other surface impoundments	☐		
5.5.4	Other disposal	☐		

SECTION 6. TRANSFER(S) OF THE TOXIC CHEMICAL IN WASTES TO OFF-SITE LOCATIONS

6.1 DISCHARGES TO PUBLICLY OWNED TREATMENT WORKS (POTWs) NA ☐

6.1.B._	POTW Name						
POTW Address							
City		County		State		ZIP	

A. Quantity Transferred to this POTW (pounds/year*) (Enter range code**or estimate)	B. Basis of Estimate (Enter code)

If additional pages of Part II, Section 6.1 are attached, indicate the total number of pages in this box ☐

and indicate the Part II, Section 6.1 page number in this box. ☐ (Example: 1, 2, 3, etc.)

6.2 TRANSFERS TO OTHER OFF-SITE LOCATIONS NA ☐

6.2.___	Off-Site EPA Identification Number (RCRA ID No.)								
Off-Site Location Name:									
Off-Site Address:									
City		County		State		ZIP		Country (non-US)	

Is this location under control of reporting facility or parent company? ☐ Yes ☐ No

EPA form 9350 -1 (Rev. 07/2011) – Previous editions are obsolete.

*For Dioxin or Dioxin-like compounds, report in grams/year.
**Range Codes: A= 1-10 pounds; B= 11-499 pounds; C= 500-999 pounds.

FORM R

Part II. CHEMICAL-SPECIFIC INFORMATION (CONTINUED)

TRI Facility ID Number

Toxic Chemical, Category, or Generic Name

6.2. TRANSFERS TO OTHER OFF-SITE LOCATION (CONTINUED)

A. Total Transfer (pounds/year*) (Enter a range code** or estimate)	B. Basis of Estimate (Enter code)	C. Type of Waste Treatment/Disposal/ Recycling/Energy Recovery (Enter code)
1.	1.	1. M
2.	2.	2. M
3.	3.	3. M
4.	4.	4. M

6.2___ Off-Site EPA Identification Number (RCRA ID No.)

Off-Site Location Name:

Off-Site Address:

City | County | State | ZIP | Country (non-US)

Is this location under control of reporting facility or parent company? Yes ☐ No ☐

A. Total Transfer (pounds/year*) (Enter a range code** or estimate)	B. Basis of Estimate (Enter code)	C. Type of Waste Treatment/Disposal/ Recycling/Energy Recovery (Enter code)
1.	1.	1. M
2.	2.	2. M
3.	3.	3. M
4.	4.	4. M

SECTION 7A. ON-SITE WASTE TREATMENT METHODS AND EFFICIENCY

☐ Not Applicable (NA) - Check here if no on-site waste treatment method is applied to any waste stream containing the toxic chemical or chemical category.

a. General Waste Stream (Enter code)	b. Waste Treatment Method(s) Sequence (Enter 3- or 4-character code(s))						c. Waste Treatment Efficiency (Enter 2 character code)
7A.1a	7A.1b	1		2			7A.1c
		3		4		5	
		6		7		8	
7A.2a	7A.2b	1		2			7A.2c
		3		4		5	
		6		7		8	
7A.3a	7A.3b	1		2			7A.3c
		3		4		5	
		6		7		8	
7A.4a	7A.4b	1		2			7A.4c
		3		4		5	
		6		7		8	
7A.5a	7A.5b	1		2			7A.5c
		3		4		5	
		6		7		8	

If additional pages of Part II, Section 6.2/7.A are attached, indicate the total number of pages in this ☐ box and indicate the Part II, Section 6.2/7.A page number in this box. ☐ (Example: 1, 2, 3, etc.)

*For Dioxin or Dioxin-like compounds, report in grams/year.
**Range Codes: A= 1-10 pounds; B= 11-499 pounds; C= 500-999 pounds.

FORM R

Part II. CHEMICAL-SPECIFIC INFORMATION (CONTINUED)

TRI Facility ID Number
Toxic Chemical, Category, or Generic Name

SECTION 7B. ON-SITE ENERGY RECOVERY PROCESSES

☐ NA Check here if no on-site energy recovery is applied to any waste stream containing the toxic chemical or chemical category.

Energy Recovery Methods (Enter 3-character code(s))

1 [ ] 2 [ ] 3 [ ]

SECTION 7C. ON-SITE RECYLING PROCESSES

☐ NA Check here if no on-site recycling is applied to any waste stream containing the toxic chemical or chemical category.

Recycling Methods (Enter 3-character code(s))

1. [ ] 2. [ ] 3. [ ]

SECTION 8. DISPOSAL OR OTHER RELEASES, SOURCE REDUCTION, AND RECYCLING ACTIVITIES

		Column A Prior Year (pounds/year*)	Column B Current Reporting Year (pounds/year*)	Column C Following Year (pounds/year*)	Column D Second Following Year (pounds/year*)
8.1					
8.1a	Total on-site disposal to Class I Underground Injection Wells, RCRA Subtitle C landfills, and other landfills				
8.1b	Total other on-site disposal or other releases				
8.1c	Total off-site disposal to Class I Underground Injection Wells, RCRA Subtitle C landfills, and other landfills				
8.1d	Total other off-site disposal or other releases				
8.2	Quantity used for energy recovery on-site				
8.3	Quantity used for energy recovery off-site				
8.4	Quantity recycled on-site				
8.5	Quantity recycled off-site				
8.6	Quantity treated on-site				
8.7	Quantity treated off-site				
8.8	Quantity released to the environment as a result of remedial actions, catastrophic events, or one-time events not associated with production processes (pounds/year*)				
8.9	Production ratio or activity index				

8.10 Did your facility engage in any newly implemented source reduction activities for this chemical during the reporting year?
If so, complete the following section; if not, check NA. **NA** ☐

	Source Reduction Activities (Enter code(s))	Methods to Identify Activity (Enter codes)		
8.10.1		a.	b.	c.
8.10.2		a.	b.	c.
8.10.3		a.	b.	c.
8.10.4		a.	b.	c.

*For Dioxin or Dioxin-like compounds, report in grams/year.

APPENDIX B

SUBMITTED TO THE SOUTH CAROLINA WATER RESOURCES JOURNAL

Visualizing Relative Potentials for Aquatic Ecosystem Toxicity Using the EPA Toxics Release Inventory and Life Cycle Assessment Methods

Theodore Langlois, Michael Carbajales-Dale, Elizabeth Carraway

AUTHORS: Department of Environmental Engineering and Earth Sciences, Clemson University, 342 Computer Court, Anderson, SC 29625, USA.

Abstract. As a result of the 1986 Emergency Planning and Community Right-to-Know Act, the U.S. EPA Toxic Release Inventory (TRI) has been available since 1987 as a record of industrial releases of toxic chemicals. Combining TRI data with estimates of relative toxicity of these chemicals to aquatic systems increases the utility of the database by providing a common basis for comparison. TRI reports masses of approximately 170 chemicals or chemical classes released to water, air, and soil. The Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) is a database of Characterization Factors (CFs) developed from chemical studies and environmental transport models to assess environmental impacts with respect to a reference compound or unit of toxicity. Using Life Cycle Assessment (LCA) techniques, these data have been combined to based tools to estimate comparative aquatic ecosystem toxicity in comparative toxicity units (CTU_e). The visualization software Tableau was used to generate representations of the preliminary results in this communication. The major potential sources of aquatic toxicity have been identified for South Carolina by industry type and by year over the period 1987-2016. The possibility of toxicity from releases of zinc compounds from power generation and pulp and paper mills far exceeds all other sources. Zinc compounds are seen to dominate the annual CTU_e over the full time period 1987-2016 with periodic decreases reflecting economic factors. Locations of releases are generally seen to occur near the major manufacturing and urban areas in the state. Trends in total CTU_e in South Carolina over 1987-2016 compared to the U.S. as a whole reveal comparative toxic effects of total releases in the state generally track the nation except for periods in the late 1990s and in the mid-2000s when toxicity was down nationally.

INTRODUCTION

While the growth of the manufacturing sector is beneficial to many aspects of South Carolina's economy, there may be unintended, negative consequences for the state's natural

resources. Direct releases of hazardous chemicals by industrial facilities to South Carolina waterways can harm species important for ecosystem health, biodiversity, and recreation. The U.S. EPA Toxics Release Inventory (TRI) tracks releases of 692 chemicals and chemical classes, but lacks specific data relevant to toxicity and environmental harm. Combining chemical evaluation methods such as those developed within the framework of Life Cycle Assessment (LCA) with TRI data can fill that gap. This communication presents initial results obtained using TRI data for freshwater in South Carolina and LCA methodologies. Developments using LCA methodologies, combined with the data visualization tool Tableau, provide additional and more nuanced information about the potential for environmental damage associated with industrial releases. The resulting tool provides a novel perspective for viewing TRI data. By utilizing the best available toxicity data and a powerful visualization tool, complex relationships between chemicals and the environment become more accessible to the public. The results enable a better understanding the potential impacts of manufacturing in the state of South Carolina and demonstrate the utility of data visualization techniques.

PROJECT DESCRIPTION

In response to the December 1984 industrial disaster at a Union Carbide plant in Bhopal, India which released approximately 40 tonnes of methyl isocyanate (CH_3NCO) gas, and smaller-scale industrial accidents in the United States, Congress passed the 1986 Emergency Planning and Community Right-to-Know Act (Broughton 2005, Koehler 2007). The law addressed the potential for incidents that could affect human health in areas surrounding chemical or industrial plants. Section 313 of this statue charged the Environmental Protection Agency with creating a list of facilities and their yearly releases of hazardous chemicals, the result being the Toxics Release Inventory. The EPA maintains a list of toxic chemicals and thresholds that, if exceeded by a facility, must be reported. The resulting database offers individuals and communities yearly, itemized reports of industrial activities and hazardous chemicals that may impact their neighborhoods. As legislation, TRI initiated a new way of regulating industry; instead of an agency enforcing limits, it provides an information network which private citizens and interest groups can use to exert pressure on polluters until they reduce toxic waste to a level the public deems acceptable (Fung and O'Rourke 2000). It is important to note that TRI does not track illegal releases, rather, it accounts for permitted releases associated with industrial processes. The program is generally agreed to be quite successful. From 1988, the second year of the program, to 1995 the total amount of toxic chemicals released or transferred decreased by about 45% (US EPA 1995).

While serving as a valuable tool for communities, the TRI does not include toxicity data within the database. Available data are presented as releases to water, air, and land by pound of chemical. Thus, a user can compare releases of mercury compounds to lead compounds only by mass, with no indication of the potential for harm. More comprehensive analysis and models are needed to assess potential risk or damage to human and ecosystem health. To some degree, EPA has remedied this knowledge gap in annual publications. Along with the TRI National Analysis, a document analyzing yearly release trends, the agency has created a risk-based model, the Risk-Screening Environmental Indicators (RSEI) which is available online for public use. The RSEI model assigns toxicity weights to chemicals that affect human health. While this model provides a measure of

toxicity, it is a risk-based model focused solely on human health.

Additionally, the EPA in 2016 released a visualization tool to present TRI data and provide outreach for its Pollution Prevention (P2) program (Gaona and Kohn 2016). The tool uses visualization and mapping software Qlik to produce useful stories valuable to the public. Although useful for communicating risk to the public, this specific tool, like the TRI itself, conveys only pounds of toxic waste managed.

Life Cycle Assessment (LCA) is a tool generally reserved for evaluating the cradle-to-grave impacts of a product or system, however, LCA provides tools useful for analysis of environmental impacts on a local, statewide, and national scale. LCA is comprised of four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. In the inventory phase, elemental flows are tracked into and out of a product system. Raw materials, water, and energy may enter the boundaries of this system, while a final product and associated emissions exit the boundary. While the TRI does not track products, it represents an inventory of chemical by-products from manufacturing. In the impact assessment phase, an LCA practitioner uses inventory results to determine what type of impact is associated with their release to the environment.

These impacts belong to either midpoint or endpoint categories. Midpoint impacts are measurables that are directly influenced by chemical releases. For example, global warming potential (GWP) is a midpoint category that greenhouse gasses directly impact, while climate change is the endpoint impact related to GWP. Multiple midpoint impacts, such as aquatic ecotoxicity, acidity, and eutrophication impact the ecosystem quality endpoint. Several models may be used to directly relate chemical releases into the environment with midpoint impacts. One such model, the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI), uses Characterization Factors (CFs) based on chemical studies and environmental transport models, to assess environmental impacts with respect to a reference compound or unit of toxicity (EPA 2012).

METHODS

In this analysis, direct-to-water releases are converted to toxicity values using their CFs found in the TRACI database. The final LCA phase, interpretation, is done through analysis and visualization using Tableau software.

TRI and TRACI data were downloaded from the EPA website, compiled into Microsoft Access databases, and imported into Tableau data visualization software for analysis (EPA 2018). The process is outlined in Figure 1.

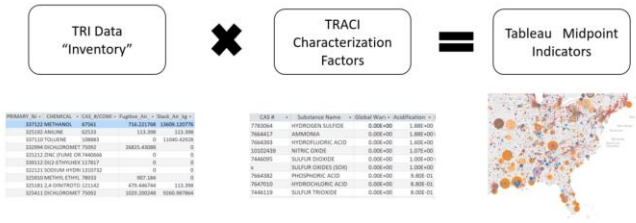


Figure 1. Data generation and visualization methodology.

Ecosystem toxicity, referred to in TRACI as ecotoxicity, is measured in comparative toxicity units (CTU_e), which are proportional to estimates of potentially affected fraction of species (PAF), integrated over time and volume, per unit mass of a chemical emitted (USEtox 2010). This calculation, shown below, allows different chemicals to be compared in terms of their potential to harm species within an ecosystem.

$$CTU_e = W(kg) * CF\left(\frac{CTU_e}{kg}\right)$$

The mass of chemical released according to the TRI database is W, measured in kilograms. The characterization factor CF, measured in CTU_e/kg, is the measure of toxicity associated with each chemical in the TRACI database. When multiplied together, using a tableau data join and in-program calculation, the product is a comparative toxicity value for each year and reporting location for each chemical or chemical class. The comparative nature of this toxicity measure must be stressed; the CTU_e is not a measure of species affected by a chemical, rather it represents a method of comparing relative toxicity across a wide range of conditions and releases.

The TRACI database includes multiple CFs for different modes of release: to air (urban or rural), water (fresh or marine), and land (agricultural or natural soil). Several assumptions must be made for consistent results. First, we assume that all chemical releases are made to freshwater. Second, since TRI data groups certain metal compounds together and TRACI does not, a proxy compound must be chosen to represent a group of compounds. The RSEI methodology document, produced by EPA, states that these compound categories are assumed to be metals in their most toxic form (US EPA 2018). Thus, the TRI category for "Copper Compounds" is associated with the TRACI chemical "Copper (II)".

RESULTS

Figure 2 presents the comparative toxicity (in millions of CTU_e) for total TRI releases to water in South Carolina between 1987 and 2016 grouped by industry sectors. A few industries and chemicals have dominated ecotoxicity to South Carolina's waterways over the past 30 years. It is clear that zinc compounds consistently present the largest ecosystem risk, especially from fossil fuel generation and paper and pulp mills sectors. Four of the top ten largest sources are related to paper or pulp manufacturing. Other significantly toxic releases include copper, vanadium, cobalt, and antimony compounds.

Figure 3 shows the annual trend in ecotoxicity risks over the history of TRI data collection, with time on the X-axis and ecotoxicity measured in CTU_e on the Y-axis. Vanadium compounds were added to the TRI list in 2000, adding to the overall yearly toxicity. Despite a general increase in production efficiency in the US, the level of toxicity released to South Carolina water bodies increased in the late 1990s and experienced another increase in the mid-2000s, most likely to an overall increase in manufacturing in the state. However, releases decreased sharply in the late 2000s, due to economic recession, which is reflected in this data (Koh et al. 2016).

Figure 4 maps locations of cumulative toxic chemical releases to South Carolina waters over 1987-2016. The distribution of TRI releases is seen to align with major manufacturing areas in the state. There are concentrations in the Spartanburg-Greenville area, the Charlotte Metro area, Georgetown, and Charleston. Many plants sit on fresh water bodies used for recreation and often drinking water supply.

Figure 5 presents a comparison of annual variability of the comparative ecotoxicity of TRI releases in South Carolina and the U.S. as a whole. Interestingly, the trends in ecotoxicity to not directly correlate between South Carolina and the rest of the United States. While ecotoxicity in the early years of TRI declined in the United States, it remained relatively low and stable in South Carolina. However, if

increases in toxic releases can be attributed to increases in manufacturing, it seems that South Carolina was ahead of the rest of the country in its increase in the late 1990s and increased again in the mid-2000s while toxicity was down nationally. Finally, the state was consistent with the rest of the country with respect to the decline in operation and subsequent toxic releases after the financial crisis of 2008. While release of hazardous materials can be tied to economic growth, especially for the manufacturing sector, it is of course not a desirable outcome. As South Carolina continues to grow its economy through industry, companies and private citizens should closely monitor environmental impacts of hazardous chemical release.

DISCUSSION

The apparent variability in toxicity levels indicates potential problems with using TRI as a marker for gains or losses in environmental protection. First, the nature of the reporting mechanisms places relatively little importance on accuracy. It is estimated that in its first year, 10,000 out of 30,000 facilities required to comply with the program failed to do so and in any given year, only 3% of facilities are investigated by EPA (Wolf 1996). Second, the sitting EPA administration has the power to add and remove chemicals on a year-by-year basis. This means that the chemical list from 1987 differs significantly from the 2016 list. Third, chemicals can change reporting categories. In one year, a chemical release or method of treatment may be listed in different category. This creates a phantom or paper reduction, in which appears as a decrease in trends, but does not in fact correspond to a physical reduction (Natan and Miller 1998). Despite reporting errors, changing categories, or addition and removal of chemicals, the analysis of TRI using Life Cycle Impact Assessment methods proves to be a powerful tool for identifying data trends.

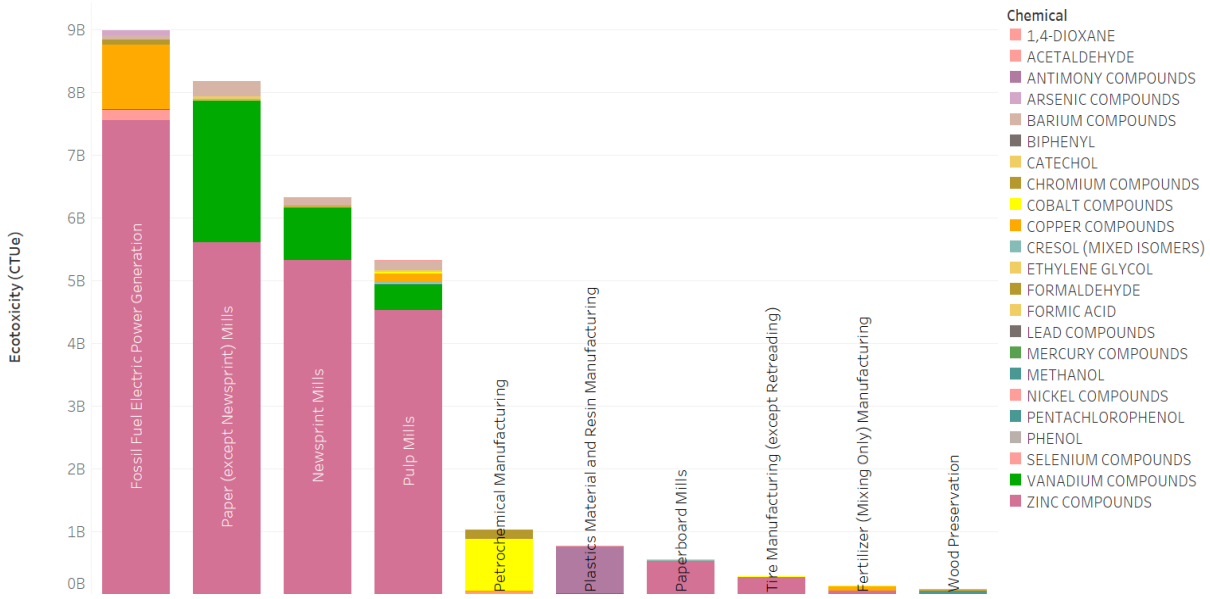


Figure 2. Top 10 industrial sectors releasing toxic chemicals to SC waterways 1987-2016.

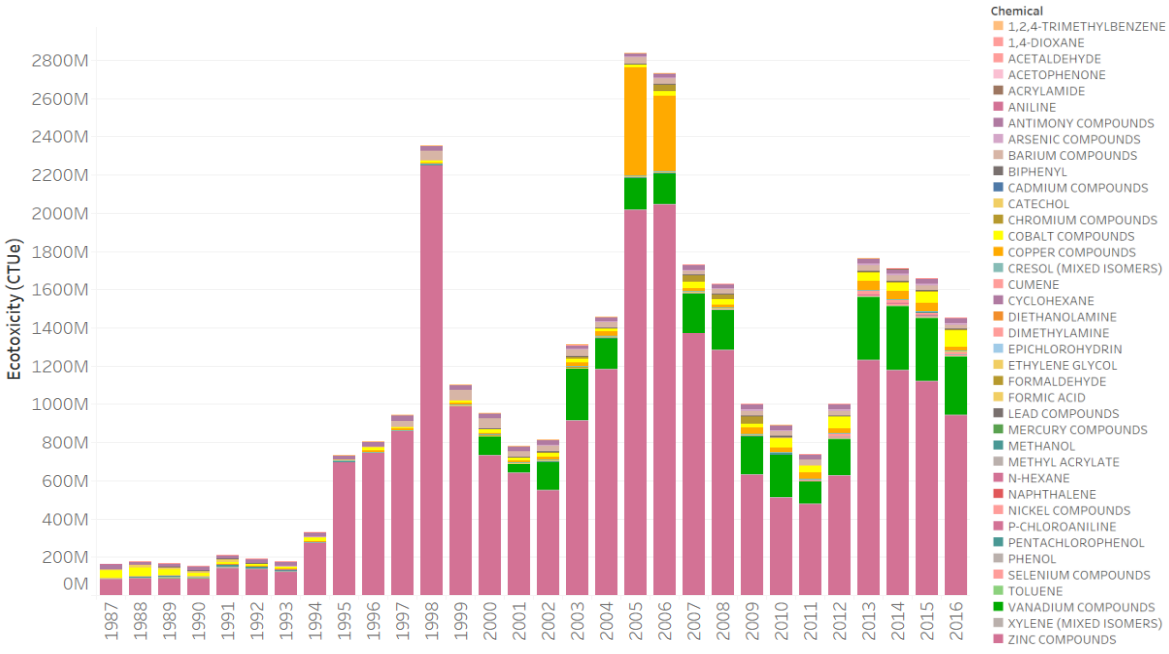


Figure 3. Annual variability of comparative ecotoxicity by chemical class.

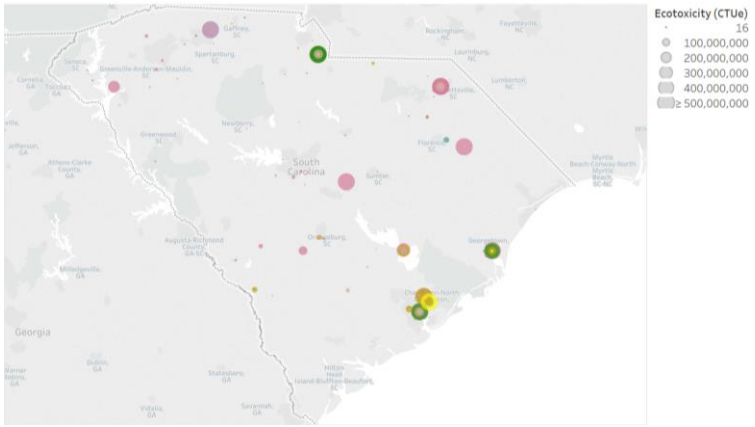


Figure 4. Comparative ecotoxicity of 1987-2016 releases from South Carolina facilities.

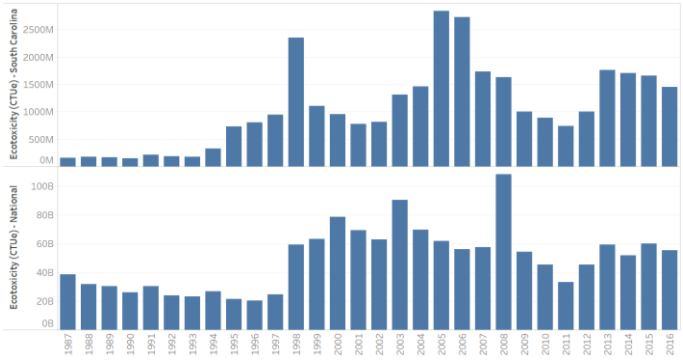


Figure 5. South Carolina and U.S. trends in comparative ecotoxicity 1987-2016.

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