Journal of South Carolina Water Resources, Volume 5, Issue 1, Pages 61–67, 2018

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

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Abstract. The U.S. EPA Toxic Release Inventory has been available since 1987 as a record of industrial releases of toxic chemicals following the 1986 Emergency Planning and Community Right-to-Know Act. Combining this release data with estimates of relative toxicity of these chemicals to aquatic systems increases the value of the database by providing a common basis for comparison. The Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts is a database of characterization factors to assess environmental impacts. It was used to develop relative ecotoxicity impacts and interpreted using Life Cycle Assessment concepts. 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 dominated the potential ecotoxicity over the full time period 1987–2016.

INTRODUCTION

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 or EPCRA (Broughton, 2005; Koehler & Spengler, 2006). The law addressed the potential for incidents that could affect human health in areas surrounding chemical or industrial plants. Section 313 of this statute charged the Environmental Protection Agency (EPA) with creating a list of facilities and their yearly releases of hazardous chemicals, the result being the Toxics Release Inventory (TRI). Since 1987, the EPA has maintained a list of toxic chemicals and thresholds that, if exceeded by a facility, must be reported. Over its 3 decades of existence, the most significant modification was the addition of more than 200 chemicals in 1994, bringing the list to more than 600 reportable chemicals and chemical categories. The resulting database offers the public itemized reports of masses of chemicals released into water, air, and soil by each facility, thus providing an annual summary of hazardous chemical releases by industrial activities. The TRI is currently available online for the years 1987 to 2016 (U.S. EPA, 1987–2017). As legislation, EPCRA and the TRI initiated a new way of regulating industry; instead of an agency enforcing limits, the approach provides an information network that 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 & 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 (Dahl, 1997; Ritter, 2015; Wolf, 1996). From 1988, the second year of the program, to 1995, the total amount of toxic chemicals released or transferred decreased by about 45% (U.S. EPA, 1987–2017).

Although it serves as a valuable tool for communities, the TRI does not reflect relative risks because toxicity information is absent within the database. Available data are presented as releases to water, air, and land by pound of chemical. Thus, using TRI data only, a user can compare releases of mercury compounds to lead compounds by mass, with no indication of which is potentially more harmful. To assess potential risk or damage to human and ecosystem health due to TRI-reported industrial releases, additional data, models, and more comprehensive analysis are needed.

To some degree, EPA has remedied this gap, through annual *TRI National Analysis* publications that analyze yearly release trends (U.S. EPA, 2018b) and through the creation of the Risk-Screening Environmental Indicators (RSEI), which is a model incorporating TRI data with measures of human exposure and toxicity (U.S. EPA, 2018a). The RSEI model assigns toxicity weights to chemicals based solely on human health effects. Additionally, the EPA in 2016 released a visualization tool to present TRI data and provide outreach for its Pollution Prevention (P2) program (Gaona & Kohn, 2016). The tool uses the visualization and mapping software Qlik-Sense (qlik.com) to aid in visual analysis of large data sets and provide better tools to the public. Although powerful in its capabilities and accessibility to nonexperts, this specific tool, like the TRI itself, conveys only pounds of toxic waste managed.

For assessment of broader environmental impacts, EPA has developed the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI; Bare 2011; Bare et al., 2002). TRACI provides factors for the estimation of chemical effects in several impact categories, for example, ozone depletion, global warming, acidification, eutrophication, and ecotoxicity. The current version of TRACI, Version 2.1, although available to the public on the EPA website, is primarily used by Life Cycle Impact Assessment practitioners and researchers (U.S. EPA, 2012). The use of TRACI requires input of data, such as TRI chemical releases; selection of options; and interpretation of impact characterization results. TRI data is not incorporated into this tool as it is in the RSEI model. TRACI also does not incorporate any visualization or mapping tools.

A few studies have combined TRI and TRACI to investigate broad applicability of the tools, as well as more specific LCA questions. No reports were found illustrating the combination of TRI, TRACI, and visualization software. Toffel and Marshall (2004) evaluated 13 weighting schemes for converting TRI data to potential environmental and human health effects and recommended EPA's products RSEI and TRACI. Lim et al. (2010) performed an in-depth analysis of 2007 TRI data coupled with human health and ecotoxicity potentials from TRACI. Their results showed that, in general, none of the chemicals identified as highest priority concerns using toxicity-based adjustments would be identified with TRI quantity-based data alone. Zhou and Schoenung (2009) illustrated the use of TRI data and an aggregation of impact assessment tools with a case study of the chemical manufacturing industry. Lam et al. (2011) identified pollution prevention options in the printed writing board manufacturing industry through analysis of TRI data, TRACI, and RSEI. Sengupta et al. (2015) examined ethanol and gasoline production processes using National Emissions Inventory data supplemented by TRI data and TRACI to estimate environmental and human health impacts.

Any combination of TRI and models such as TRACI generates numerical results and adds to the mass of environmentally related data available. To deal with large amounts of data, scientists, data analysts, and businesses are increasingly turning to visualization tools to provide data insights and inform decision making (Helbig et al., 2017; Palomino et al., 2017). These tools allow users to more easily extract important information from large datasets (Keim et al., 2008). It is a logical progression to use these tools to present data in an online and user-navigable format. This approach is consistent with the original mission of the TRI system, which is to provide the public with access to environmental data. The combination of visualization software with toxicity and environmental data can enhance the TRI program's availability and utility. Among several visualization software packages available, Tableau has been recognized as outstanding among commercial products (Nair et al., 2016). While the full Tableau product is a proprietary commercial product, Tableau Public (public.tableau.com) is a free product and online gallery that allows users to upload their visualizations and data sets for others to use or to connect to data files and create visualizations.

PROJECT DESCRIPTION

This communication presents initial results in the development of an online visual data tool combining TRI data, TRACI ecotoxicity impact factors, LCA methodologies, and Tableau visualizations. The utility of this combination is illustrated for industrial toxic chemical releases to freshwater in South Carolina. LCA methodology was developed to help users understand relationships between the physical flow of chemicals and energy. Within the context of reports to TRI, it can be useful to combine LCA methods with a data management and visualization tool such as Tableau to generate innovative and useful data insights. With coincident freshwater resources and manufacturing industries, South Carolina represents an interesting case for the use of the combined tool.

LCA is generally reserved for evaluating the cradle-to-grave impacts of a product or system; however, it provides tools useful for analyzing environmental impacts on a local, statewide, and national scale (Zampori et al., 2016). LCA is composed 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. Although the TRI does not track products, it represents an inventory of chemical byproducts from manufacturing. In the impact assessment phase, an LCA practitioner uses inventory results to determine the types of impacts associated with releases 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 is a midpoint category impacted by greenhouse gasses, whereas climate change is the endpoint impact related to global warming potential. Multiple midpoint impacts, such as aquatic ecotoxicity, acidity, and eutrophication, affect the ecosystem quality endpoint. Several models may be used to directly relate chemical releases into the environment with midpoint impacts. In this study, TRACI's Characterization Factors (CFs), which are based on chemical toxicity studies and environmental transport models, are used to assess potential environmental impacts in terms of a mass of a reference compound or relative units of toxicity (U.S. EPA, 2012).

METHODS

In this analysis, direct-to-water releases from TRI are converted to ecotoxicity midpoint impact values using relevant CFs in the TRACI database. The final LCA phase, interpretation, is done through analysis and visualization using Tableau software (Version 2018.2, tableau.com). TRI and TRACI data were downloaded from the EPA website, compiled into Microsoft Access databases, and imported into Tableau for analysis (U.S. EPA, 1987–2017; U.S. EPA, 2012). The overall process is outlined as TRI data "inventory" × TRACI CFs = Tableau midpoint indicators.

Ecosystem toxicity, referred to in TRACI as ecotoxicity, is given by

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

where CTU_e is the comparative toxicity unit for ecotoxicity; W is the mass of chemical released according to the TRI database, measured in kilograms; and CF is the measure of ecotoxicity associated with each chemical in the TRACI database, measured in CTU_e/kg. CTU_e values are proportional to estimates of potentially affected fractions of species, integrated over time and volume, per unit mass of a chemical emitted (USEtox, 2010). This calculation allows different chemicals to be compared in terms of their potential to harm species within an ecosystem. When multiplied together, using a Tableau data join and in-program calculation, the product is a comparative ecotoxicity value for each year and reporting location for each chemical or chemical class. The comparative nature of this ecotoxicity measure must be stressed; the CTU_e is not a specific prediction of effects on species by a chemical; rather, it represents a method of relating expected ecotoxicity 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). Some assumptions must be made to choose CFs and generate comparable results. First, we assume that all chemical releases to water in South Carolina in the TRI database were made to freshwater and selected CFs for freshwater. Second, because 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 (U.S. EPA, 2018) states that these compound categories are assumed to be metals in their most toxic form. Thus, the TRI category for "Copper Compounds" is associated with the TRACI chemical "Copper (II)."

RESULTS

Figure 1 illustrates the dramatic difference in the chemicals that contribute most to TRI-reported releases to freshwater in South Carolina when assessed by mass and CTU_e. Results are shown for 2016. The data shown in Part A were adapted from the 2016 EPA National Analysis Results for South Carolina, whereas those presented in Part B are results generated by the tool developed in this project. Nitrate compounds clearly dominate by a wide margin in terms of mass of releases but do not appear when adjusted to reflect potential ecotoxicity effects.

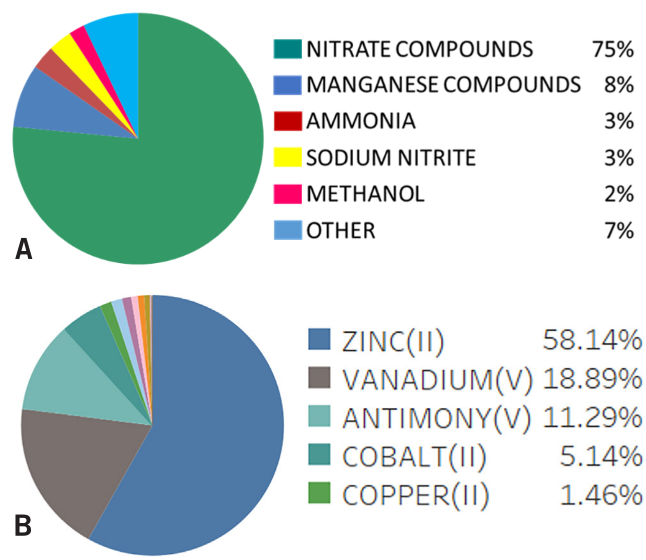

Figure 1. Top 5 releases to freshwater in South Carolina in 2016 by (A) mass as reported by the Toxics Release Inventory and (B) ecotoxicity.

For a broader perspective, Figure 2 presents the comparative toxicity (in millions of CTU_e) for total TRI-reported releases to freshwater 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 the paper and pulp mill sectors. Four of the top 10 largest sources are related to paper or pulp manufacturing. Other significantly toxic releases include copper, vanadium, cobalt, and antimony compounds.

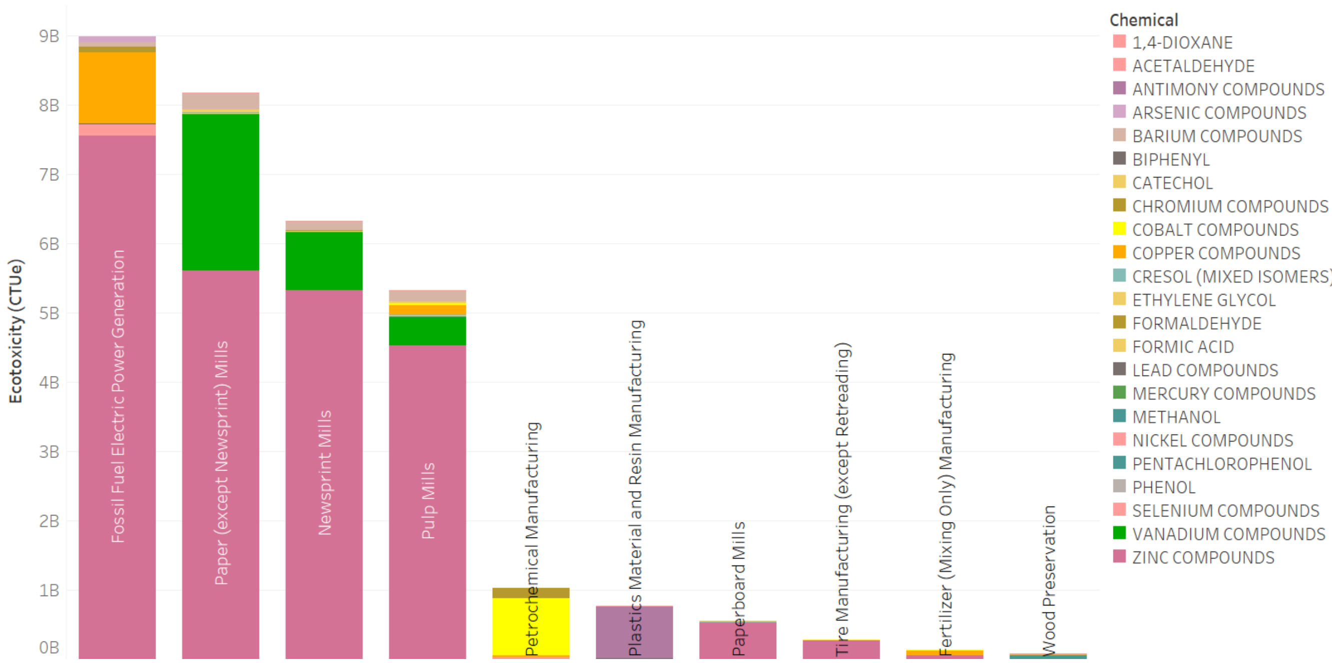

Figure 2. Top 10 industrial sectors releasing toxic chemicals to South Carolina waterways, 1987–2016. CTU = comparative toxicity unit.

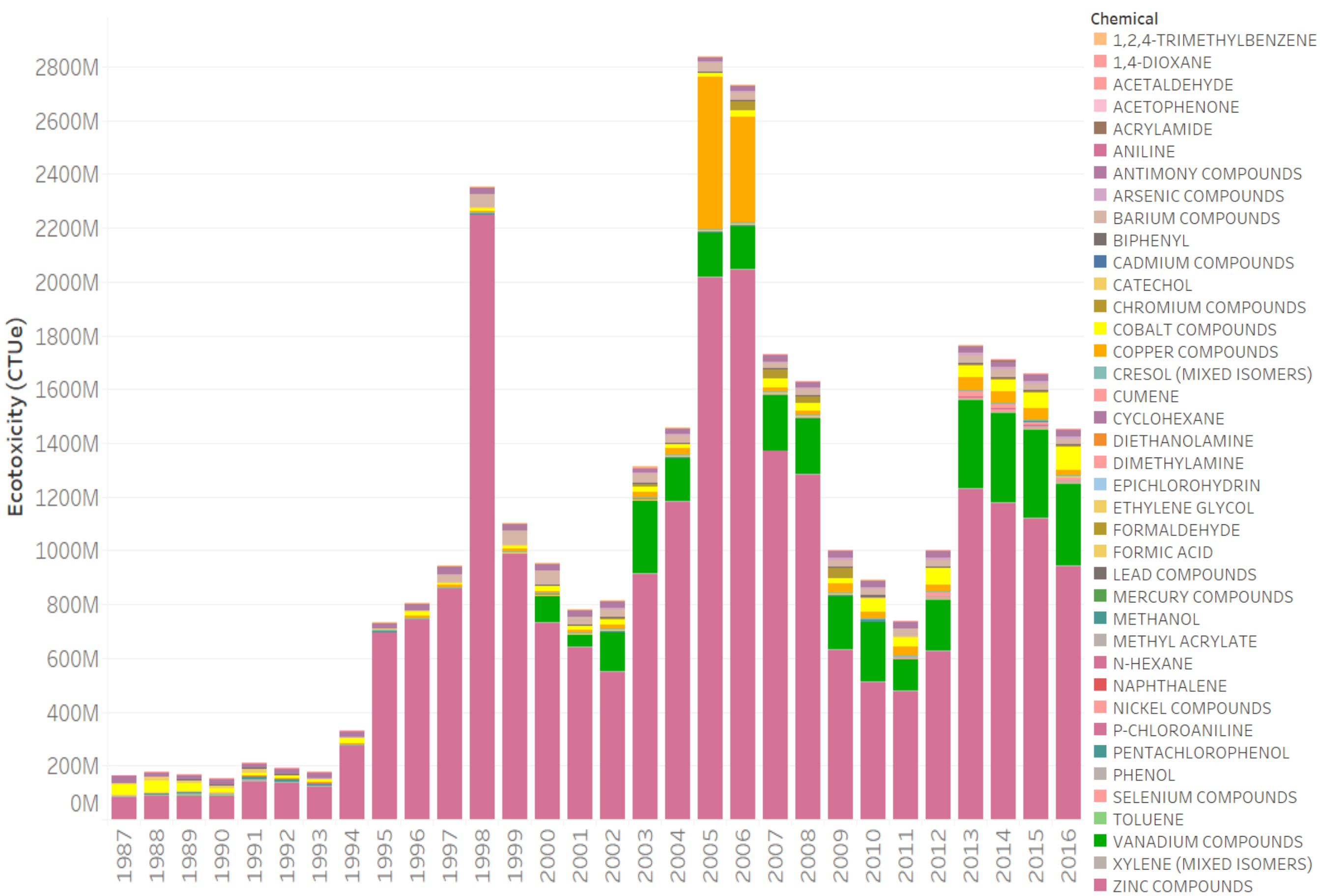

Figure 3. Annual variability of comparative ecotoxicity by chemical class. CTU = comparative toxicity unit.

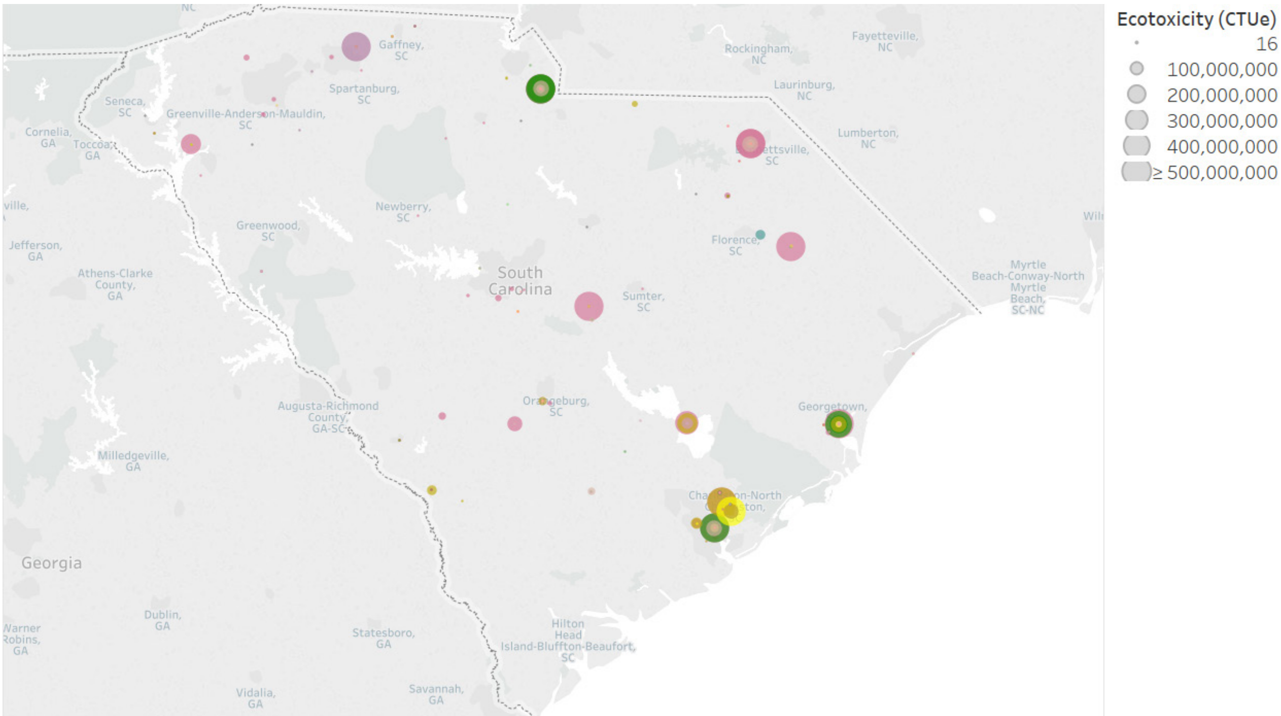

Figure 4. Comparative ecotoxicity of releases from South Carolina facilities, summed over 1987–2016. CTU = comparative toxicity unit.

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 United States, 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 due to an overall increase in manufacturing in the state. However, releases decreased sharply following the economic recession, which is reflected in this data (Koh et al. 2016).

Figure 4 maps locations of toxic chemical releases to South Carolina waters summed over 1987–2016. The distribution of TRI-reported releases aligns with major manufacturing areas in the state. There are concentrations in the Spartanburg–Greenville area, the Charlotte metro area, Georgetown, and Charleston. Many plants are near freshwater bodies used for recreation and drinking water supply.

Figure 5 presents the annual variability of comparative ecotoxicity from TRI-reported releases in South Carolina and the United States as a whole. Interestingly, the trends in ecotoxicity do not directly correlate between South Carolina

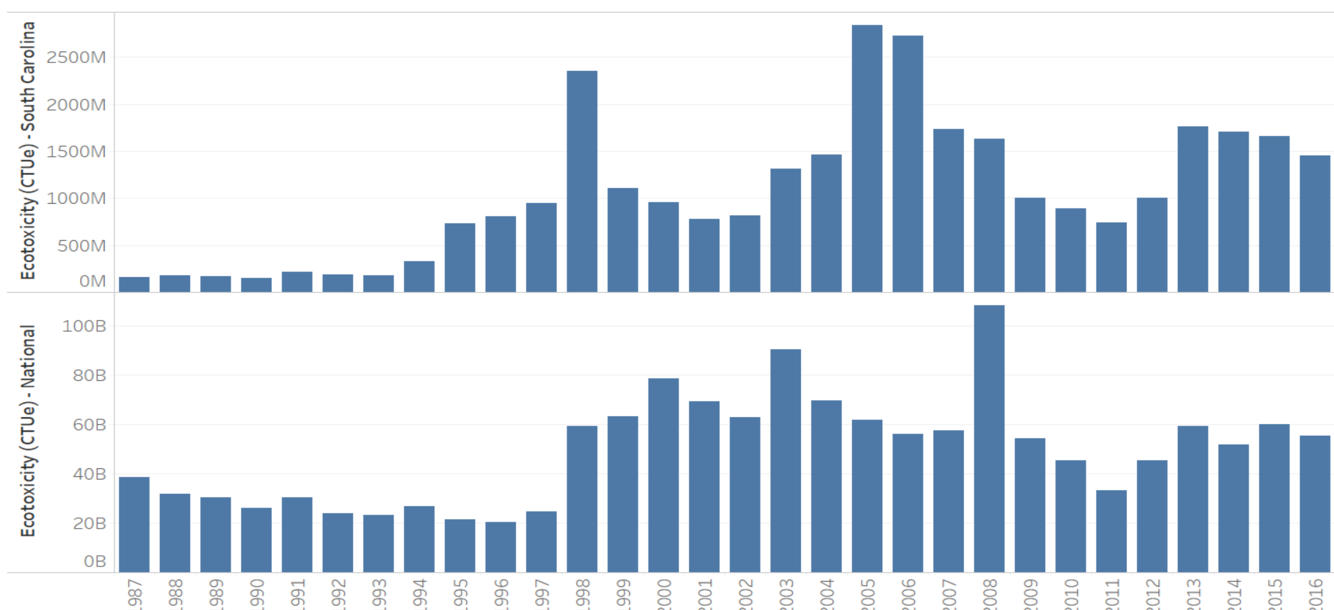

Figure 5. South Carolina and U.S. trends in comparative ecotoxicity, 1987–2016. CTU = comparative toxicity unit.

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. The years 1998, 2005, and 2006 are significant in that they show sharp increases for South Carolina, while national trends were smoother or trending downward. These points could be further investigated to determine potential influences such as changes in reporting rules or activities of specific industries in the state. 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. Although 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 mechanism 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 a different category from the next. This creates a phantom or paper reduction, which appears as a decrease in trends but does not in fact correspond to a physical reduction (Natan & Miller, 1998). Despite reporting errors, changing categories, and adding or removing chemicals, the TRI database is a valuable source for tracking industrial chemical releases. The illustrations of using LCA and visualization techniques for freshwater releases in South Carolina show the importance of including toxicity factors when assessing potential impacts to ecosystems. In particular, this analysis predicts that chemicals containing zinc exert more harm than those containing nitrate.

ACKNOWLEDGEMENTS

The authors wish to thank the Pollution Prevention Program of U.S. EPA Region 4 for support of P2 activities related to this work.

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