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UNDERSTANDING WATER TREATMENT CHEMICAL SUPPLY CHAINS AND THE RISK OF DISRUPTIONS

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Disclaimer

The Water Infrastructure and Cyber Resilience Division of the Office of Groundwater and Drinking Water has reviewed and approved the report "Understanding Water Treatment Chemical Supply Chains and the Risk of Disruptions" for publication in February 2023. This document is intended for use by the Water and Wastewater Systems Sector to better understand the risk of disruptions in the supply of water treatment chemicals. It may provide information useful for conducting *Risk and Resilience Assessments*, as required under America's Water Infrastructure Act (AWIA) of 2018.

AWIA, Section 2013 requires community water systems (CWS) serving more than 3,300 people to conduct *Risk and Resilience Assessments*, which must consider important system assets, including chemical storage and utilization. This report demonstrates that there are risks to the supply of critical water treatment chemicals, and that these risks vary by chemical. Furthermore, the local risks for a specific water system may differ from the national risks presented in this report. Thus, water systems may want to consider the risk of disruptions in their supply of the water treatment chemicals during future AWIA *Risk and Resilience Assessments*.

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Questions concerning this document should be addressed to SupplyChainSupport@epa.gov or the following contact:

Steve Allgeier
U.S. EPA Water Infrastructure and Cyber Resilience Division
26 West Martin Luther King Drive
Mail Code 140
Cincinnati, OH 45268
(513) 569-7131
Allgeier.Steve@epa.gov

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- Aileen Bressman, Cadmus
- Melissa Brown-Rosenbladt, Cadmus
- Kyrien Edwards, Cadmus
- Josh McGhee, Cadmus

Peer review of this document was provided by the following individuals:

- Andrew Barienbrock, Ohio Environmental Protection Agency, Division of Drinking and Ground Waters
- Robyn Brooks, The Chlorine Institute
- Ryan Coby, Idaho National Laboratory, Infrastructure Assurance and Analysis Division
- Kevin Morley, American Water Works Association
- Jeffrey Sloan, American Chemistry Council
- David Travers, U.S. EPA, OGDW, Water Infrastructure and Cyber Resilience Division

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

Acronym	Definition
ACC	American Chemistry Council
ATSDR	Agency for Toxic Substances and Disease Registry
AWIA	America's Water Infrastructure Act
AWWA	American Water Works Association
CAS No.	Chemical Abstracts Service Number
CBI	Confidential Business Information
CDR	Chemical Data Reporting
COVID-19	Coronavirus Disease of 2019
CWS	Community Water System
DADMAC	Diallyldimethylammonium chloride
DOE	U.S. Department of Energy
DOJ	U.S. Department of Justice
EPA	U.S. Environmental Protection Agency
FTC	U.S. Federal Trade Commission
HS	Harmonized System
HTS	Harmonized Tariff Schedule
LOX	Liquid Oxygen
NIAC	National Infrastructure Advisory Council
NSF/ANSI	National Standards Foundation / American National Standards Institute
OGDW	Office of Groundwater and Drinking Water
SDWA	Safe Drinking Water Act
TSCA	Toxic Substances Control Act
USGS	U.S. Geological Survey
USITC	U.S. International Trade Commission
WARN	Water/Wastewater Agency Response Network
WITS	World Integrated Trade Solutions

1 INTRODUCTION

1.1 Background

Drinking water and wastewater systems rely on the consistent delivery of water treatment chemicals to maintain operations and provide essential services to the public. An interruption to chemical supply, whether short-term or long-term, can have a significant impact on a system's ability to provide safe drinking water and treat wastewater prior to discharge.

Drinking water and wastewater treatment use a variety of chemicals to effectively treat water. Important types of water treatment chemicals include coagulants, disinfectants, acids, bases, corrosion inhibitors, dechlorination chemicals, and fluoridation chemicals. While there are typically multiple options for chemicals used in a particular unit process, the selected chemicals and associated feed equipment are often customized for the water quality being treated, the target treatment objectives, safety considerations, and cost considerations. Additionally, chemicals used for water treatment may be required to meet specific standards and regulations. Compliance with the National Standards Foundation/American National Standards Institute (NSF/ANSI 60) standards is required for almost all drinking water treatment chemicals used in the U.S. Many wastewater systems specify adherence to American Water Works Association (AWWA) Standards when requesting bid proposals for chemical supply agreements. Collectively, these constraints and requirements can significantly limit the pool of available chemicals that can be used by water systems and may limit flexibility to turn to other available supplies in the face of a shortage.

To better understand the supply challenges facing the Water and Wastewater Systems Sector (i.e., the water sector) and to identify which vulnerabilities may be prominent for a given chemical, supply chain profiles were developed for 46 chemicals used directly in water treatment or as precursors or raw materials used in the manufacture of those water treatment chemicals. Each profile includes information about typical uses in water treatment, competing uses, domestic manufacturing processes, domestic production and consumption, distribution of manufacturing and supply locations, history of supply disruptions, and an assessment of the risk of future disruptions. The complete profiles for each of these 46 chemicals can be found at Water Treatment Chemical Supply Chain Profiles. This report presents a synthesized analysis of these 46 chemical supply chain profiles to support a greater understanding of water treatment chemical supply chain dynamics and the risk of supply disruptions. Such an understanding may prompt greater preparedness for and resilience to supply chain disruptions within the water sector.

The U.S., though able to manufacture many of the 46 chemicals studied, is highly reliant on imports for many raw materials and precursor chemicals used to manufacture direct-use water treatment chemicals. Furthermore, even in cases where the U.S. has significant manufacturing capacity for a given chemical, captive consumption, a process in which the chemical produced is used directly by the same manufacturing entity to produce derivative chemical products, may consume a significant fraction of the quantity produced. In situations where supply chains are stressed, these dynamics in production, consumption, and import can present challenges to the reliable supply of chemicals needed for water treatment.

There have been few published studies attempting to characterize the supply chain for water treatment chemicals. The following summarizes the previous work deemed most relevant to the objectives and scope of the current study.

Henderson et al. (2009) reviewed the risk of shortage for 11 commonly used water treatment chemicals in the U.S. Their study covered a period of economic expansion in the U.S. (2003-2007), when water treatment chemical shortages were largely driven by high demand that exceeded supply followed by a period of severe economic contraction (The Great Recession of 2007-2009). Under these conditions supply chain disruptions were more pronounced for water treatment chemicals that are byproducts of an industry that experienced a contraction in demand. For example, water fluoridation chemicals, which are a byproduct of fertilizer production, were in short supply when the demand for phosphate-based fertilizers decreased significantly. During the period of 2003-2007, their study found that increased cost of manufacturing inputs, such as energy, raw materials, along with increased foreign demand were drivers of significant water treatment chemical price increases as well as occasional supply disruptions.

A 2015 report published as a collaboration between the UK Water Industry Research and the Water Research Foundation (Dillon et al., 2015) included a review of 20 water treatment chemicals used in the greatest quantity in England. The study focused on alternative chemicals with potential supply chain concerns as one approach to reducing risk. The study period included events encountered in the years prior to 2014, including the Great Recession of 2007-2009, and focused on chemical supply chains in the UK. The study findings suggest that many chemicals would most likely be available to the UK water sector during a short-term shortage, albeit at an elevated price. The authors identified geographic concentration of raw materials and the percentage of the chemical market provided for water treatment to be important long-term risk factors for continued chemical supply. As part of the risk analysis, the authors included measures reflecting price volatility, availability of chemical alternatives, impact of the loss of the chemical to water treatment requirements, and measures of security of the supply chain. Based on the risk ranking conducted as part of the study, phosphoric acid was identified as the highest risk chemical, followed by polyamines, chlorine, and polydiallyldimethylammonium chloride (polyDADMAC).

In a 2016 report from the National Infrastructure Advisory Council (NIAC) on water sector resilience (Baylis et al., 2016), a specific recommendation was made to identify and define agency and utility roles and responsibilities during an emergency to ensure continued supply of critical water treatment chemicals. The report highlighted the dependence of the water sector on other sectors, including the chemical industry, and made clear that forming partnerships across sectors could lead to an understanding of resource prioritization needs in circumstances where this may be required.

These studies demonstrate vulnerabilities in production and distribution of water treatment chemicals, and the resulting risk of disruptions in supply of critical water treatment chemicals. However, the studies have been limited in scope and do not capture the severe, and multifaceted supply chain disruptions that started at the beginning of the COVID-19 pandemic. The supply disruptions that have occurred during the pandemic era revealed a range and intensity of supply chains stressors that had not previously been observed in such a short timeframe. While high-impact events such as a pandemic or repeated extreme weather events concentrated on industrial hubs may have been considered low-probability in previous assessments, supply chain risk planning may have to consider greater frequency and cooccurrence of such high-impact events. This report attempts to provide a comprehensive and current (as of 2022) picture of the risk of disruptions in the supply of critical water treatment chemicals.

1.2 Purpose and Scope

Disruptions in the supply of water treatment chemicals discussed in the previous section, as well as those experienced between March 2020 and the date of publication of this report, demonstrate the need for the water sector to develop a better understanding of chemical supply chains and their risk of experiencing supply disruptions in the future.

The purpose of this report is to present the results from a risk evaluation of the supply chain for the 46 chemicals listed in **Table 1-1**. The chemicals researched include 35 chemicals that are directly used in water treatment in critical unit processes such as disinfection, coagulation, corrosion control, and dechlorination (of treated wastewater). The other 11 chemicals are raw materials or precursors necessary to produce one or more of the 35 selected water treatment chemicals. While the list of chemicals presented in **Table 1-1** is not comprehensive of all chemicals used in water treatment or used to manufacture water treatment chemicals, the selected chemicals are representative of a broad range of water treatment chemicals and their precursors.

The results of this study can help the water sector anticipate and prepare for possible supply chain disruptions and inform an analysis of supply chain risks for individual water systems as part of a *Risk and Resilience Assessment*, such as those required under America's Water Infrastructure Act (AWIA), Section 2013. Additionally, the results of this study can provide insight into the availability of water treatment chemicals, in terms of both producers and suppliers. This information also has value to the implementation of Section 1441 of the Safe Drinking Water Act (SDWA), Assurance of Availability of Adequate Supplies of Chemicals Necessary for Treatment of Water. If the U.S. Environmental Protection Agency (EPA) determines that a water treatment chemical is not reasonably available, it may issue a certification of need to prioritize water systems for access to available supplies (EPA, 2022a).

1.3 Document Overview

The remainder of this report is organized into the following major sections:

- **Section 2** provides an overview of the methodology used to develop chemical profiles and conduct a relative risk evaluation
- **Section 3** provides a discussion of factors that can lead to supply disruptions, case studies of disruptions in the supply of water treatment chemicals, and results of the relative risk evaluation
- **Section 4** provides a summary of the key findings from this study
- **Section 5** describes the practical applications of the results of this study, for federal agencies as well as individual water systems
- **References** lists all sources used in this study
- **Glossary** provides definitions for terminology used in this report
- **Appendix A** provides the quantitative rating scales used to perform the relative risk evaluation

Table 1-1. Water Treatment Chemicals and Precursors Considered in this Study

Chemical Name	CAS No.	Treatment Applications	Derivative Water Treatment Chemicals (Treatment Application)
Acrylamide	79-06-1	None identified	Polyacrylamide (PAM) (coagulation)
Aluminum Hydroxide	21645-51-2	None identified	Aluminum sulfate (coagulation) Polyaluminum chloride (coagulation)
Aluminum Sulfate	10043-01-3	Coagulation	None identified
Ammonium Hydroxide	1336-21-6	Used to form chloramines for residual disinfection	None identified
Anhydrous Ammonia	7664-41-7	Used to form chloramines for residual disinfection	Ammonium hydroxide (residual disinfection) Carbon dioxide, a byproduct of ammonia production (pH adjustment)
Bauxite	1318-16-7	None identified	Aluminum-based coagulants
Calcium Carbonate	1317-65-3	pH and alkalinity adjustment	Calcium oxide (softening)
Calcium Hydroxide (Slaked Lime)	1305-16-0	pH and alkalinity adjustment	Calcium hypochlorite (disinfection)
Calcium Hypochlorite	7778-54-3	Disinfection	None identified
Calcium Oxide (Quick Lime)	1305-78-8	Precipitative softening	Calcium hydroxide (pH adjustment)
Carbon Dioxide	124-38-9	pH adjustment	None identified
Chlorine	7782-50-5	Disinfection Algal control Onsite generation of chlorine dioxide	Hydrochloric acid (pH adjustment) Sodium hypochlorite (disinfection) Calcium hypochlorite (disinfection) Ferric chloride (coagulation) Ferrous chloride (coagulation)
Citric Acid	77-92-9	Membrane cleaning	None identified
Diallyldimethylammonium chloride (DADMAC)	7398-69-8	None identified	PolyDADMAC (coagulation)
Disodium Phosphate	7558-79-4	Corrosion control	Sodium polyphosphates (corrosion control)
Ferric Chloride	7705-08-0	Coagulation	None identified
Ferric Sulfate	10028-22-5	Coagulation	None identified
Ferrous Chloride	7758-94-3	Coagulation	Ferric chloride (coagulation)
Ferrous Sulfate	7720-78-7	Coagulation	Ferric sulfate (coagulation)
Fluorosilicic Acid	16961-83-4	Fluoridation	None identified

Chemical Name	CAS No.	Treatment Applications	Derivative Water Treatment Chemicals (Treatment Application)
Hydrochloric Acid	7647-01-0	pH adjustment Regeneration of ion-exchange resins	Polyaluminum chloride (coagulation) Ferric chloride (coagulation) Ferrous chloride (coagulation) Zinc orthophosphate (corrosion control)
Hydrogen Peroxide	7722-84-1	Oxidation Dechlorination	Sodium chlorite (chlorine dioxide production)
Ilmenite	98072-94-7	None identified	Ferric chloride (coagulation) Ferrous sulfate (coagulation)
Manganese Ore	1313-13-9	None identified	Potassium permanganate (oxidation)
Monosodium Phosphate	7558-80-7	Corrosion control	Sodium polyphosphates (corrosion control)
Oxygen	7782-44-7	On-site generation of ozone Aeration	Sulfur dioxide (dechlorination) Sulfuric acid (pH adjustment)
Phosphate Rock	1306-05-4	None identified	Fluorosilicic acid (fluoridation) Phosphoric acid (corrosion control)
Phosphoric Acid	766-38-2	Corrosion control pH adjustment	Sodium ortho- and polyphosphates (corrosion control) Zinc orthophosphate (corrosion control)
Polyaluminum Chloride	101707-17- 9	Coagulation	None identified
Potassium Chloride	7447-40-7	None identified	Chlorine (disinfection) Potassium hydroxide (pH adjustment)
Potassium Hydroxide	1310-58-3	pH adjustment	Potassium permanganate (oxidation)
Potassium Permanganate	7722-64-7	Oxidation	None identified
Silica	7631-86-9	Filtration media	Sodium silicate (corrosion control)
Sodium Carbonate	497-19-8	pH and hardness adjustment	Sodium phosphates (corrosion control) Sodium silicate (corrosion control)
Sodium Chlorate	7775-09-9	None identified	Sodium chlorite (chlorine dioxide generation) Chlorine dioxide (disinfection)
Sodium Chloride	7647-14-5	On-site generation of sodium hypochlorite Regeneration of ion-exchange resin	Chlorine (disinfection) Sodium hydroxide (pH adjustment)

Chemical Name	CAS No.	Treatment Applications	Derivative Water Treatment Chemicals (Treatment Application)
Sodium Chlorite	7758-19-2	On-site generation of chlorine dioxide	None identified
Sodium Hydroxide	1310-73-2	pH adjustment Precipitation of metals	Calcium hypochlorite (disinfection) Disodium phosphate (corrosion control) Monosodium phosphate (corrosion control) Sodium hypochlorite (disinfection) Sodium silicate (corrosion control) Sodium chlorite (chlorine dioxide generation)
Sodium Hypochlorite	7681-52-9	Disinfection Algal control	None identified
Sodium Salts of Polyphosphates	10124-56-8 68915-31-1 7758-79-4 7558-80-7	Corrosion control	None identified
Sodium Silicate	6834-92-0	Corrosion control	None identified
Sulfur	7704-34-9	None identified	Sulfur dioxide (dechlorination) Sulfuric acid (pH adjustment)
Sulfur Dioxide	7446-09-5	Dechlorination	Sodium metabisulfite (dechlorination) Sodium thiosulfate (dechlorination)
Sulfuric Acid	7664-93-9	pH adjustment Regeneration of ion exchange resins	Aluminum sulfate (coagulation) Ferric sulfate (coagulation) Ferrous sulfate (coagulation) Fluorosilicic acid (fluoridation) Phosphoric acid (corrosion control) Zinc Orthophosphate (corrosion control)
Zinc	7646-85-7	None identified	Zinc Orthophosphate (corrosion control)
Zinc Orthophosphate	7779-90-0	Corrosion control	None identified

A profile was developed for each treatment chemical, precursor, and raw material listed in **Table 1-1**. according to the methodology described in **Section 2.1**. These profiles are available at Water Treatment Chemical Supply Chain Profiles.

2 METHODOLOGY

This section provides an overview of the methodology employed in the supply chain research and profile development for the chemicals listed in **Table 1-1**. The resulting supply chain profiles provided the input to the relative risk evaluation. The methodology used to develop the risk evaluation framework is discussed below in **Section 2.3**.

2.1 Treatment Chemical Profiles

Research into the supply chains for water treatment chemicals relied extensively on publicly available resources developed by the U.S. government, industry groups, trade organizations, journal publications, and other credible sources. In some instances, individual companies and water systems were contacted to gain additional insights and to validate information gathered through other sources. The following subsections describe the process used to develop the water treatment chemical supply chain profiles, which serve as the basis for the analysis and findings in this report.

2.1.1 Applications in Water Treatment

Water treatment application information was primarily gathered from the AWWA document library. Where chemicals have an associated AWWA Standard, the Standard was reviewed for background on accepted use for drinking water. Other primary sources included textbooks such as *Wastewater Engineering* by Metcalf & Eddy, the National Center for Biotechnology Information’s PubChem database, and producer/manufacturer websites which may contain detailed information on applications of their products. NSF International, which certifies drinking water treatment chemicals, served as an additional source of information on typical application. A secondary source of information regarding chemical use, including applications and specifications, was obtained through a search of requests for proposals (RFPs) published by municipalities or water utilities for the purchase of water treatment chemicals.

2.1.2 Other Applications

The National Center for Biotechnology Information’s PubChem database of chemical molecules served as a primary resource for information on the variety of applications for a given chemical. The Agency for Toxic Substances & Disease Registry (ATSDR) provides detailed profiles for numerous hazardous substances, including some direct-use water treatment chemicals and their precursors. Additional information about the uses of chemicals was gathered from EPA and U.S. Geological Survey (USGS) publications, American Chemistry Council publications, trade associations such as the Aluminum Association and the Chlorine Institute, and chemical manufacturer websites which list specific application for their products.

The USGS National Minerals Information Center publications served as the primary source of information on raw material uses.

2.1.3 Manufacturing Process

PubChem served as a primary resource for information on the manufacturing method(s) of a given chemical. Additional resources consulted to characterize manufacturing methods include manufacturer publications, and websites of trade organizations such as the Chlorine Institute. If distinct grades or purity are required for water treatment applications, the additional manufacturing steps required to achieve the desired purification were investigated.

2.1.4 Domestic Production

Estimates of total domestic production were based on one of several government sources or trade organization sources. The first primary government source consulted for most chemicals is data collected as part of the Chemical Data Reporting (CDR) rule under the Toxic Substances Control Act (TSCA). The CDR rule requires manufacturers (including importers) to provide EPA with information on the production of chemicals in commerce. This information includes the types and quantities of chemical substances produced domestically. The information is collected every four years and represents annual production volumes of 25,000 lbs. or greater. However, companies may submit a request to designate production volume as confidential business information (CBI), and due to acceptance of these requests, CDR data can underestimate actual domestic production. Furthermore, some chemicals, such as those manufactured for non-TSCA uses, are exempt from reporting. The majority of production data collected was obtained from the 2020 CDR dataset and reflects data for 2019 (EPA, 2020). There were some instances in which data from the 2016 CDR dataset (which reflects data collected for 2015) was used instead, due to an increase in CBI claims or other concerns with the 2020 CDR dataset for a given chemical.

The USGS National Minerals Information Center publications served as the primary source of information on raw material production volumes. Available information includes yearly mineral industry surveys and commodity summaries, which provide domestic production and consumption statistics for the past five years, as well as trade, trends, and any marketplace issues of note.

In instances where the two primary resources listed above could not provide chemical production data, industry publications, journal articles, and news items were reviewed.

2.1.5 Domestic Consumption

Values for total domestic consumption were unavailable from the publicly available resources used for this study, thus, total domestic consumption was estimated using one of several primary sources.

- For chemicals with relatively complete CDR data (i.e., few CBI reporting exemptions), domestic consumption was estimated by subtracting total domestic exports from the sum of estimated domestic production and imports for consumption.
- The USGS National Minerals Information Center publications served as the primary source of information on domestic consumption of raw materials.
- For chemicals with incomplete CDR data, other resources were used to estimate domestic consumption, including: publications from federal agencies such as USGS, EPA, and U.S. Department of Energy (DOE); publications for relevant trade organizations, such as *gasworld*, the *American Chemistry Council*, or *WaterWorld*; ATSDR profiles, which often include data on consumption; and internet searches on consumption patterns, both broadly as well as specific to the water sector.

2.1.6 Trade and Tariffs

Trade data was considered from two perspectives: international trade among all countries, and domestic import and export.

Worldwide import and export data were collected through the World Integrated Trade Solution (WITS) database. The WITS database is a compilation of data from international sources including the World Bank, United Nations Conference on Trade and Development, United Nations Statistical Division, and World Trade Organization. The WITS database provides worldwide import and export data for commodities at the level of the international 6-digit Harmonized System (HS) commodity classification code. General imports and total exports measure the total movement of goods in and out of a country. This resource was used to determine the largest importing and exporting countries (by quantity), and the status of the U.S. in relation to all other reporting countries.

Domestic import and export data were collected through the U.S. International Trade Administration Commission (USITC) DataWeb, which provides U.S. trade and tariff data for commodities based on the Harmonized Tariff Schedule of the United States (HTS), which is a hierarchical system that builds on the 6-digit HS coding system, subdividing goods into 8-digit and 10-digit categories, as explained through an example below. For this research, analysis focused on subsets of general imports and total exports. Imports for consumption, representing a subset of general imports, encompass total commodity volume that has cleared U.S. customs for consumption. Domestic exports, representing a subset of total exports, encompass total commodity volume produced or manufactured in the U.S. and commodities of foreign origin modified in the U.S. These trade categories were chosen to more accurately assess the quantity of goods associated with U.S. production activities. In addition to quantity of traded goods, information on trading partners was collected.

Differences in trade classification codes at the 6-digit vs. 8- or 10-digit level may lead to different reporting categories for a given chemical. For example, ferric chloride is categorized in the HTS system by an 8-digit code, 2827.39.55, which encompasses solely chlorides of iron. The HS system, used in this study to characterize international trade, uses a 6-digit categorization (2827.39) and includes chlorides of iron as one group of several chlorides apart from those of magnesium, aluminum, and nickel. Instances where this distinction may impact the trade volumes reported were considered and noted. Duty estimates were obtained using the most recent publication of the USITC HTS Tariff Schedule.

2.1.7 History of Shortages

Research for this study investigated previous supply disruptions that occurred over the period of 2000 to 2022. Disruptions identified through this research were characterized as widespread or regional, depending on their geographic extent. Less severe supply disruptions were also captured, including issuance of force majeure, systemic delivery delays, significant and repeated price increases, challenges in obtaining key inputs as reported by manufacturers and suppliers, and issues related to price fixing and Sherman Act violations.

Key resources were identified for a review of market history, and include the following:

- News stories
- Industry publications
- Bid documents and water utility news items
- Force majeure notices
- USITC briefings and investigations
- U.S. Federal Trade Commission (FTC) cases and proceedings
- U.S. Department of Justice (DOJ) antitrust cases
- Communications with manufacturers and suppliers
- Direct reporting to EPA

2.2 Information Resources

Due to the unique nature of each chemical supply chain, distinct resources were used to research each chemical. However, several common resources provided a foundation for this study. These common resources are briefly described here.

American Chemistry Council (ACC): A trade organization representing a diverse set of companies engaged in the chemical industry including domestic chemical companies and the plastics and chlorine industries. The ACC website offers basic information on the manufacturing, handling, and storage of a variety of chemicals. https://www.americanchemistry.com/default.aspx

National Institutes of Health - PubChem Database: PubChem is a database of chemical molecules. The system is maintained by the National Center for Biotechnology Information, a component of the National Library of Medicine, which is part of the U.S. National Institutes of Health. This source was used to obtain basic chemical information and determine use and manufacturing information. https://pubchem.ncbi.nlm.nih.gov/

The National Standards Foundation (NSF) International: NSF International is a non-governmental standard setting and testing organization. NSF/ANSI Standard 60 provides standards and a certification program for almost all direct and indirect drinking water additives. The standard, referred to as NSF/ANSI 60 specifies testing and evaluation criteria to ensure that drinking water treatment chemicals meet globally accepted public health standards, and is one of the most widely used and commonly accepted standards for drinking water treatment chemicals in the U.S. NSF International provides a database of certified suppliers and products for NSF/ANSI 60 certified chemicals. http://info.nsf.org/certified/pwschemicals/

The Chlorine Institute: A technical trade association of companies involved in the production, distribution and use of chlorine, sodium and potassium hydroxide, sodium hypochlorite, and hydrochloric acid. The Chlorine Institute provides product stewardship documents, manufacturing pamphlets, and manufacturing data for select chemicals. https://bookstore.chlorineinstitute.org/

U.S. Department of Health and Human Services, Public Health Service, Agency for Toxic Substances and Disease Registry (ATSDR): ATSDR provides toxicological profiles which characterize the toxicologic and adverse health effects information for select toxic substance. Each peer-reviewed profile identifies and reviews the key literature that describes a substance's toxicologic properties. https://www.atsdr.cdc.gov/

U.S. Environmental Protection Agency Chemical Data Reporting (CDR) Rule: The CDR rule, under the Toxic Substances Control Act (TSCA), updated every four years, requires EPA to compile information from manufacturers and importers of chemicals used in commerce. Under the rule, EPA collects basic information on the types, quantities and uses of chemical substances produced domestically and imported into the U.S. The CDR was used as a primary source for estimating domestic production of chemicals considered in this study. https://www.epa.gov/chemical-data-reporting

U.S. Geological Survey (USGS) - Mineral Commodity Summaries: Published on an annual basis, this report is the earliest government publication to furnish estimates covering nonfuel mineral industry data. Data sheets contain information on the domestic industry structure, government programs, tariffs, and 5-year salient statistics for more than 90 individual minerals and materials. These summaries were used as a source of information about raw materials researched as part of this study. Information collected includes trade data, production and consumption amounts, typical uses, and historical supply chain disruptions. https://www.usgs.gov/centers/nmic/mineral-commodity-summaries

U.S. Geological Survey Minerals Yearbook: These annual publications review the mineral industries of the United States and of more than 180 other countries. They contain statistical data on minerals and materials and include information on economic and technical trends and developments. The Yearbook was used as a source of background information on available raw materials. https://www.usgs.gov/centers/nmic/minerals-yearbook-metals-and-minerals

U.S. International Trade Commission (USITC) DataWeb: The USITC DataWeb provides U.S. merchandise trade and tariff data. Trade data for 1989 to the present are available on a monthly, quarterly, annual, or year-to-date basis and can be retrieved using a querying tool with features such as user defined country and commodity groups. The USITC DataWeb was the primary source for domestic import and export data. https://dataweb.usitc.gov/

U.S. International Trade Commission (USITC) Harmonized Tariff Schedule (HTS): The USITC HTS provides a web-based system to search the most recently published edition of the HTS. https://hts.usitc.gov/

World Integrated Trade Solution (WITS): The WITS database is a compilation of data from international sources including the World Bank, United Nations Conference on Trade and Development, United Nations Statistical Division, and World Trade Organization. The WITS database provides worldwide import and export data for commodities at the level of the 6-digit HS commodity classification code and allows users to access and retrieve information on trade and tariffs. The WITS database was the primary for international import and export data. https://wits.worldbank.org/

2.3 Relative Risk Evaluation Framework

The information compiled in the supply chain profiles developed using the process and resources described in **Section 2.1** and **Section 2.2**, respectively, was used to conduct a relative risk evaluation of the 46 chemicals considered in this study. The framework is based on a variation of the standard risk equation, as defined in the following figure.

Relative Risk = Criticality x Likelihood x Vulnerability	
Criticality	Measure of the importance of a chemical to the water sector
Likelihood	Measure of the probability that the chemical will experience a supply disruption in the future, which is estimated based on past occurrence of supply disruptions
Vulnerability	Measure of the market dynamics that make a chemical market more or less resilient to supply disruptions

The standard risk equation uses the parameters consequence, threat, and vulnerability (AWWA, 2021a), while this study replaced consequence with criticality and threat with likelihood to better reflect the risk drivers for chemical supply chains. In order to assess risk, it is necessary to quantify, or at least characterize each of the risk parameters, however, the authors were unable to identify a formalized methodology for doing so in the context of chemical supply chain disruptions. Rather, a new approach for quantifying the risk parameters was developed for this study based on an analysis of the supply chains and a review of historic disruptions in these supply chains.

A framework was established to develop ratings for the three risk parameters, which are multiplied to yield a relative risk rating for each chemical. The framework assigns values to the factors identified as being important to each of the risk parameters. A rating scale was established for each factor in a manner to create a reasonable spread in the resulting ratings. Once the initial risk parameter ratings were computed for all 46 chemicals, the distribution of values was analyzed. If the values clustered at one end of the distribution, adjustments were made to the rating scale to provide a useful distribution. While this rating framework is based on an analysis of factors that demonstrably impact supply chain risk, the rating scale is based on professional judgement and thus there is a degree of subjectivity in the development of the scale. Other frameworks could produce equally valid results. However, the risk evaluation framework used in this study provides a meaningful assessment of relative risk of supply chain disruptions among the 46 chemicals, within the assumptions of this methodology. The following sections provide details about the factors used to evaluate each of the three risk parameters. The numeric rating scales used to assign values to the risk parameters are presented in **Appendix A**.

2.3.1 Criticality

While "Consequence" is the standard term used in the widely accepted form of the risk equation, for this supply chain relative risk evaluation, "Criticality" is a more appropriate and inclusive parameter. Criticality is a measure of the importance of a specific chemical to the water sector, either as a direct use chemical for treatment of drinking water (raw or finished) or wastewater or as a precursor to the production of direct use treatment chemicals. The attributes of the chemical used to assess its criticality include: (1) unit processes in which the chemical is used; (2) extent of use of the chemical in treatment; and (3) number of applications, including both direct use in treatment and as a precursor. The lowest rating possible is given to a chemical with a limited number of applications, limited use in water treatment, and typically used in periodic applications rather than on a regular basis. Chemicals with a high criticality rating are those that have widespread use in water treatment, are necessary to produce treated water compliant with regulations, and are used as precursors in the production of other water treatment chemicals.

2.3.2 Likelihood

"Likelihood," in the context of a risk evaluation, is defined as the probability that conditions will occur that produce an undesirable outcome. In this relative risk evaluation of supply chains, likelihood is the probability that a disruption in the supply of a chemical will occur. A common method of assessing likelihood as part of a risk evaluation is to use past occurrence as a proxy for future occurrence, and this is the method used in this study. Specifically, occurrence of the following types of supply disruptions between 2000 and 2022 was used to assign a value to the likelihood risk parameter: (1) previous widespread disruption to domestic supply; (2) previous supply disruptions isolated to a region; (3) previous invocation of force majeure clauses in supply contracts or concerns about potential supply disruptions; (4) history of significant price increases; and (5) no known supply disruption.

2.3.3 Vulnerability

"Vulnerability," in the context of a risk evaluation, is defined as the characteristics of an asset that provide opportunity for it to experience an undesirable outcome. In this supply chain risk evaluation, vulnerability considers the characteristics of the broad domestic market for a specific chemical that make it more or less resilient to supply disruptions. The attributes of chemical markets that were used to assess the vulnerability of a chemical market to a supply disruption include: (1) Import dependence and trade policies; (2) U.S. production diversity; (3) domestic competition for supply; and (4) stability of the chemical in storage. The lowest vulnerability rating possible represents a chemical widely produced in the U.S. in quantities necessary to meet domestic consumption, with limited dependence on imports, limited competition from other markets, and long shelf life. The highest rating possible is assigned to a chemical produced at a limited number of locations within the U.S. in quantities insufficient to meet domestic consumption, high tariffs on countries that are major producers of the chemical, and competition from other critical sectors.

2.3.4 Relative Risk Rating Categorization

To facilitate analysis, the ratings for the criticality, likelihood, and vulnerability risk parameters, as well as the overall relative risk rating, were grouped into equally sized bins, as shown in **Figure 2-1**. The moderate bin is further divided in half to create moderate-low and moderate-high bins. Grouping of chemicals into these bins is not intended to present an absolute characterization and ranking of chemicals by their risk of experiencing supply disruptions, but rather to illustrate which chemicals have characteristics that may place them at greater or lesser risk of supply disruptions relative to one another.

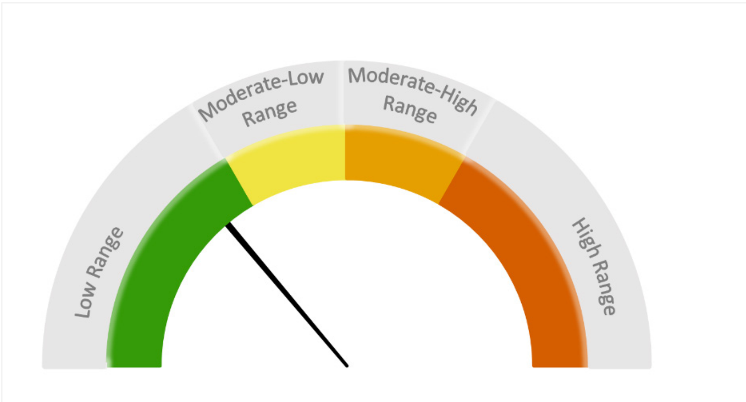


Figure 2-1. Relative Risk Rating Bins

2.4 Data Review and Quality Control

To ensure the data is of a quality necessary to support the study objectives, steps were taken to ensure the validity and integrity of the information from the time it was collected through analysis. The procedures for data source selection gave preference to sources that are reputable, well-documented, and peer-reviewed. Data sources were also categorized by the level of accurate information they offer (e.g., sources maintained by EPA and other government organizations or are otherwise reputable and well-documented, sources that are peer-reviewed, sources that present measured rather than estimated quantities). Data partially behind a paywall or otherwise incomplete information was not utilized.

A standardized data collection process was established for all data elements collected. To maximize the comparability of common data elements across chemicals, each data element was populated from the same data source or from other data sources considered in the priority order described above. Consistent data formatting and a standardized set of units were established.

Data quality was evaluated based on availability, completeness, and transparency. Quality control activities included an evaluation of accuracy by comparison of the same data element obtained from multiple, independent sources, where possible. Data was rejected if determined to lack the accuracy or completeness needed to support the study objectives. In some cases, subject matter expertise was utilized to evaluate the suitability of data for a particular analysis. Limited data gaps did not necessarily preclude development of a chemical profile or completion of the relative risk evaluation.

2.5 Study Limitations

One of the more significant limitations encountered while collecting data for this study was varying levels of data availability and completeness. Data availability for manufacturing methods and locations, domestic production, domestic consumption, and trade categorization varied among the chemicals researched. Some of the specific challenges encountered include:

- Manufacturing Methods: Some chemicals, as manufactured for water treatment, have trade-secret manufacturing methods or other barriers to understanding the domestic manufacturing process.
- Production Data: In some instances, there was limited or no production data available, and in other instances there were limitations to the available production datasets. This included a high degree of CBI

for select CDR datasets, limited sources of information for chemicals with no production data collected under the CDR rule, and inconsistencies between two or more sources of production data.

- Production for the Merchant Market: Chemicals used for water treatment are part of merchant market consumption, and thus the portion of total domestic production destined for the merchant market is of greatest interest for this study. However, there were sparse data available for most chemicals to distinguish between quantities of domestic production destined for captive consumption vs. merchant market consumption. Thus, the profiles and relative risk evaluation typically use total domestic production, total imports, and total consumption.
- Trade Data: As noted in Section 2.1.6, trade categories can often refer to a group or groups of chemicals rather than a specific chemical. This makes import and export data for such a category an estimate of trade for a specific chemical among several. Additionally, items coded by the international HS system vs. the domestic HTS system may include different groupings of chemicals. Trade categorization of a chemical was occasionally unclear in cases where the trade category does not specify the chemical name. In these cases, supporting documentation was sought to attempt to identify the appropriate category. In other instances, assigned trade categories for complex chemicals are sometimes inconsistently used by foreign importers, making it unclear whether a given trade category provides a clear and accurate assessment of the trade for a specific chemical rather than a broad category of chemicals.
- Domestic Consumption Data: While this data was available directly from USGS for raw materials and could be calculated using the method described in Section 2.1.5 for most chemicals with available production data, generally there were no independent methods of verifying consumption data. In cases where trade data represents a larger class of chemicals that the chemical of interest falls within, consumption estimates likely have a wide margin of error.

Market Accessibility

Captive Consumption: Chemicals manufactured and internally consumed by a given entity or subsidiary for further manufacturing.

Merchant Market Consumption: Chemicals manufactured by a producer and sold to another entity.

With an understanding of these limitations, a relative risk evaluation framework was developed to use the available data to estimate relative risk of future supply disruptions (see Section 2.3 for full discussion of the methodology). The accuracy of the results from the relative risk evaluation depends on the availability of data used to rate the three risk parameters. In cases in which the target data were unavailable or incomplete, qualitative information was collected and used to estimate the factors needed to develop a rating for the risk parameters. Furthermore, the relative risk evaluation framework is a construct that simplifies highly complex supply chain dependencies. The results provide a relative, not absolute, estimate of risk and are intended only to provide some insight regarding characteristics and vulnerabilities of each supply chain that may warrant further evaluation and analysis.

While the study researched 46 chemicals used directly in water treatment or as precursors or raw materials, this is not an exhaustive list of chemicals used in water treatment or their precursors and raw materials. There may be additional chemicals that can be included as precursors or derivatives of the chemicals researched. Inclusion of additional chemicals in the assessment could impact not only the relative risk evaluation for the 46 chemicals included in this study, but more broadly our understanding of the factors and conditions that can drive chemical supply disruptions.

3 RESULTS AND DISCUSSION

Results from the analysis of risks to the supply chain for water treatment chemicals are presented in the following subsections:

3.1	Provides a summary of the conditions leading to supply disruptions
3.2	Presents case studies of specific water treatment chemical supply disruptions
3.3	Presents findings from the relative risk evaluation of water treatment chemicals and associated raw materials and precursors

3.1 Conditions Leading to Supply Disruptions

Most water treatment chemical supply chains rely on multiple inputs at multiple steps in the manufacturing and distribution process. Often, numerous raw materials are used to manufacture a single end product. This can create complex interdependencies and may lead to increased risk of supply disruptions.

While there is not a "typical" supply chain that can represent all water treatment chemicals, the supply chain for aluminum sulfate (alum) can serve to illustrate the complexities and dependencies of a given supply chain. Production of alum relies on three inputs at different phases of production: bauxite, sodium hydroxide, and sulfuric acid, as shown in **Figure 3-1.** Aluminum hydrate, extracted from mined bauxite, is dissolved in sodium hydroxide to precipitate aluminum hydroxide. Subsequent reaction of aluminum hydroxide with sulfuric acid yields crystalized aluminum sulfate. The U.S. is almost entirely reliant on imports for non-metallurgical uses of bauxite. While the U.S. is a major producer of chemicals required at two of three steps of alum production, there is competition among domestic consumers of these precursors (sodium hydroxide and sulfuric acid). Domestic competition for these inputs, along with considerations of pricing and availability, may drive alum manufactures to rely on import from a variety of countries, as depicted in the figure. Furthermore, production of chemicals at each step in the manufacturing process may take place at different geographic locations within the U.S. or abroad, and transport of precursors may be required to manufacture the final product.

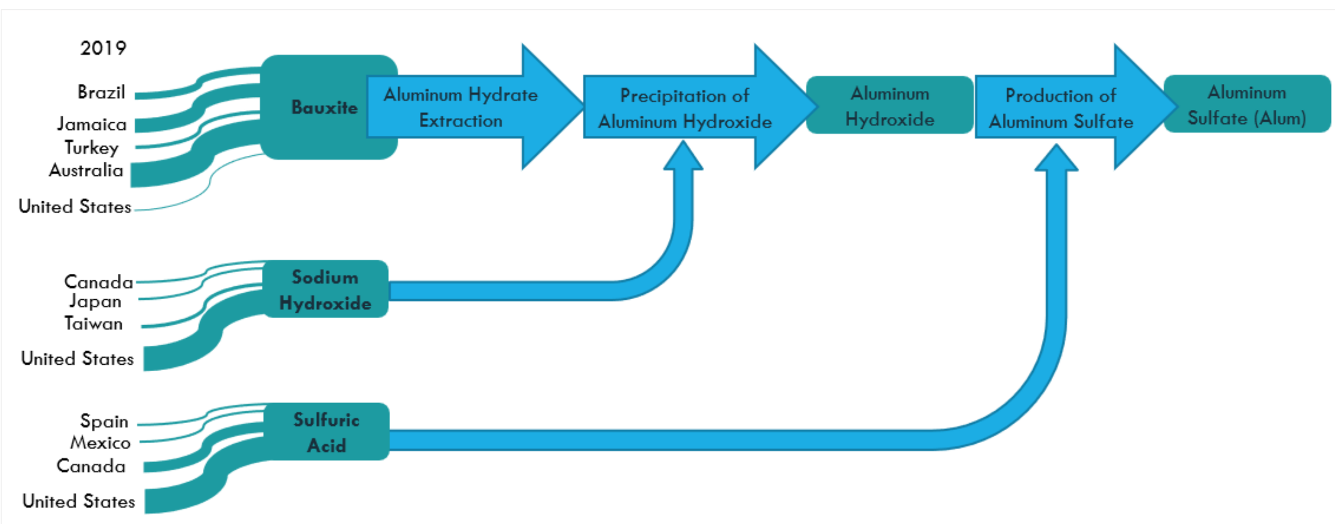


Figure 3-1. Sourcing of Raw Materials and Precursors to Manufacture Aluminum Sulfate

Most chemicals researched as part of this study are similar to alum in that they require multiple manufacturing steps, and chemicals with multiple production steps may have multiple inputs from a variety of sources.

Many chemical supply chains span multiple countries and multiple continents, which introduces a wide array of vulnerabilities. This chain of interdependencies, coupled with practices such as just-in-time inventory, creates an environment in which failure of a single link can result in a series of cascading impacts on downstream supply chains.

Analysis of significant chemical supply chain disruptions between 2020 and 2023 revealed common conditions that lead to supply disruptions and events or circumstances that cause those conditions, as summarized in **Table 3-1**.

Table 3-1. Supply Disruptions for Direct-Use Water Treatment Chemicals (2020 – 2023)

Chemical	Year	Conditions Leading to Disruption	Cause of those Conditions
Carbon Dioxide	2020	• Decrease in output of co-dependent products (e.g., ethanol, ammonia) due to a sudden decrease in demand for those products	• Global pandemic • Planned maintenance of facilities that manufacture the co-dependent products
Chlorine	2021	• Decrease in production capacity • Sudden increase in demand • Inadequate logistics	• Global pandemic • Extreme weather / natural disaster • Change in business drivers leading to planned reductions in production capacity
Sodium Hydroxide	2021	• Decrease in production capacity (co-produced with chlorine during the chlor-alkali process) • Inadequate logistics	• Global pandemic • Extreme weather / natural disaster • Change in business drivers leading to planned reductions in production capacity
Sodium Hypochlorite	2021	• Sudden change in demand • Insufficient supply of precursor material (i.e., chlorine and sodium hydroxide) • Inadequate logistics	• Volatility in the supply of key precursors
Hydrochloric Acid	2021	• Insufficient supply of precursor material (i.e., chlorine) • Inadequate logistics	• Volatility in the supply of key precursors
Ferric Chloride / Ferrous Chloride	2021	• Insufficient supply of precursor material (i.e., chlorine, hydrochloric acid, scrap iron, spent steel pickling liquor) • Inadequate logistics	• Volatility in the supply of key precursors
Oxygen	2021	• Sudden increase in demand • Inadequate logistics	• Global pandemic
Fluorosilicic Acid	2021	• Disruptions in production of precursors or co-dependent products • Competition for domestically produced precursor materials (i.e., phosphate) • Inadequate logistics	• Extreme weather • Geographic concentration of precursor materials
Chlorine, among others	2022	• Inadequate logistics due to embargoes on rail transport of hazardous materials	• Impasse in negotiations between rail carriers and unionized rail workers
Potassium Permanganate	2023	• Complete loss of domestic production capacity	• Severe fire damage to the only domestic production facility

Table 3-1 reveals four recurring conditions that lead to supply chain disruptions: decrease in production, insufficient supply of precursor materials, sudden change in demand, and inadequate logistics. Each of these conditions is briefly described below.

3.1.1 Decrease in Production Capacity

Availability of chemical production capacity that is sufficient to meet market demand is necessary for a predictable supply of water treatment chemicals. From 2020 through 2022, measures to combat the COVID-19 pandemic led to temporary closures of manufacturing facilities across the globe and a resulting decrease in production capacity for a variety of goods. Additional conditions that have led to reduced production capacity include natural disasters, mechanical failures, cyberattacks, and inadequate transportation resources. In cases where water treatment chemicals are manufactured by a small number of producers, the temporary or permanent contraction in output at just a few facilities can have a large impact on product availability. Reduced chlor-alkali production capacity in 2021 resulted in shortages of chlorine and sodium hypochlorite, as discussed in **Section 3.2.1**.

3.1.2 Insufficient Supply of Precursor Materials

Availability of precursor materials for chemical production is necessary for a predictable supply of water treatment chemicals. Whether due to geographic concentration of precursor materials, reliance on foreign sources, competition for access, or logistics challenges that make transport of available resources impractical or impossible, supply of raw or precursor materials can be strained or interrupted. The reduced chlor-alkali production capacity in 2021 discussed in the previous section also resulted in shortages of derivative products including ferric chloride, as discussed in **Section 3.2.2**.

3.1.3 Sudden Change in Demand

Chemical production capacity and distribution may not be able to adjust at a pace commensurate with rapid and unexpected changes in demand. Numerous chemicals used in water treatment are used across other industries that may experience fluctuations in demand, which can result in market volatility. These conditions developed in the liquid oxygen (LOX) market in 2021 when an unprecedented increase in demand for LOX by the health care sector led to an abrupt and significant decrease in available LOX for the water sector, as described in the case study presented in **Section 3.2.4**. Supply and demand dynamics can also impact chemical supply chains in less obvious ways. For example, **Section 3.2.2** described how reduced demand for steel resulted in decreased availability of spent pickle liquor, which is a necessary precursor in the most common production method for ferric chloride. As a third example, decreased demand for gasoline during the early stages of the COVID-19 pandemic resulted in decreased demand for ethanol, which in turn resulted in a shortage of carbon dioxide, as discussed in **Section 3.2.3**.

3.1.4 Inadequate Logistics

Regular, uninterrupted transport of chemicals is necessary for a predictable supply of water treatment chemicals. All supply chains require efficient and effective logistics to function, and while the detailed requirements vary across industries, they all require transportation and workforce. Efficient transport requires the infrastructure and workforce to move material through ports, rail exchanges, and other transportation nodes.

A 2021 survey of domestic chemical manufacturers by the American Chemistry Council cited transportation and logistics challenges as significant impairments to the domestic chemical manufacturing sector, with 99% of respondents indicating that supply chain and freight transportation disruptions had impacted their business in the year prior. Of the respondents, 96% indicated reliance on import of materials for production via ocean shipping. In some instances, companies needed to change shipping methods to avoid additional delays, and survey respondents reported that shipping delays had impacted overseas partners' production schedules. Labor shortages were cited as a significant factor in transportation delays (American Chemistry Council, 2022).

Discussions with domestic chemical suppliers have highlighted transportation and logistics challenges as significant supply chain disruptors. Workforce issues, including the lack of commercial drivers certified to haul hazardous chemicals, a temporary halt to training new drivers and train conductors during pandemic-related business closures, and other causes leading to a lack of rail and truck operators, were cited. Additional logistics challenges mentioned include delays at ports of entry, shipping challenges and delays, and pandemic-related border restrictions. Inadequate logistics played some role in all the case studies presented in **Section 3.2**.

Threat of a Nationwide Interruption in Rail Carrier Service

In September of 2022, U.S. rail carriers and unions were negotiating the terms of new contracts. As the deadline of September 16, 2022 approached without agreement, the imminent threat of an interruption in rail carrier service raised concerns about impacts on critical supply chains. On September 12, in anticipation of a potential interruption in service, rail carriers began issuing embargos on the transport of hazardous materials, including several water treatment chemicals. Transport by rail is a significant means of distribution and supply of numerous water treatment chemicals. These embargoes would likely have resulted in shortages of chlorine within 10 days, and shortages of other water treatment chemicals[1] occurring days or weeks later. Fortunately, a tentative agreement was reached before the deadline, and transport of hazardous materials resumed before shortages occurred. In November, Congress and the President enacted a law to enforce the contract tentatively agreed to on September 16, thus ending the threat of a nationwide stoppage of rail carrier service.

[1]Other water treatment chemicals that are primarily transported by rail include: sodium hydroxide, sodium hypochlorite, sulfuric acid, hydrochloric acid, phosphoric acid, liquified carbon dioxide, anhydrous ammonia, ferric chloride, and ferrous chloride.

3.2 Case Studies of Water Treatment Chemical Supply Disruptions

Analysis of the supply chain disruptions identified during this research revealed common conditions that lead to supply disruptions, as summarized in **Table 3-1.** In this section, selected supply disruptions are discussed in more detail.

3.2.1 Chlorine and Sodium Hypochlorite

Chlorine and sodium hypochlorite are the two most widely used disinfectants in drinking water and wastewater treatment. Chlorine is primarily produced through the chlor-alkali process, which uses electrolysis of sodium chloride to produce chlorine, sodium hydroxide, and hydrogen (although less common, other chloride salts, such as potassium chloride, can be used.) Sodium hypochlorite is commonly produced by reacting chlorine with sodium hydroxide. The U.S. produces over 99% of the chlorine it consumes and imports a small percentage of chlorine to meet U.S. demand, primarily from Canada. Approximately 75% of chlorine produced in the U.S. is used in the manufacture of plastics and other polymeric materials and inorganic chemicals, while approximately 9% is used for water disinfection (including industrial applications) (Kreuz et al, 2022). Domestic chlor-alkali producers Olin and Axiall (Westlake) have indicated that looking to the future, the amount of chlorine dedicated to integrated chlorovinyl and other higher-value derivative products may increase based on demand for these products (Slater, 2020; Axiall, 2013). It is estimated that in 2022 only 32% of domestic chlorine production was allocated to the merchant market. Of this, water treatment accounted for 27% of merchant market use (Kreuz et al., 2022).

As of 2019, there were 49 known chlor-alkali production facilities in the U.S. distributed across 24 states; however, 16 (33%) of these production facilities are concentrated along the Gulf Coast, an area historically prone to extreme weather events (Kaskey, 2017). Case in point, Winter Storm Uri directly hit the Gulf Coast region in February 2021, resulting in a temporary loss in chlor-alkali production capacity of approximately 28% (Chlorine Institute, 2021). Additionally, in spring and summer of 2021, several chlor-alkali production facilities experienced significant equipment failures resulting in additional, temporary losses in production capacity. While some of these impacted facilities were located in the Gulf Coast region, others were located in West Virginia, Utah, and Washington. Later in the summer of 2021, there was a permanent reduction in chlor-alkali production capacity at facilities located in New York, Alabama, Louisiana, and Texas as a result of changing business priorities. These temporary and permanent changes in domestic production capacity are shown in **Figure 3-2**. The reductions in chlor-alkali production capacity that occurred in 2021 were compounded by the impacts of COVID-19, which had resulted in decreased output of chlor-alkali chemicals by as much as 24% beginning in April 2020. There were also reports of truck and driver shortages impacting all parts of the supply chain. Additionally, rail lines were temporarily blocked in the western United States due to wildfires, forcing reroutes that delayed deliveries (Kaplan, 2021).

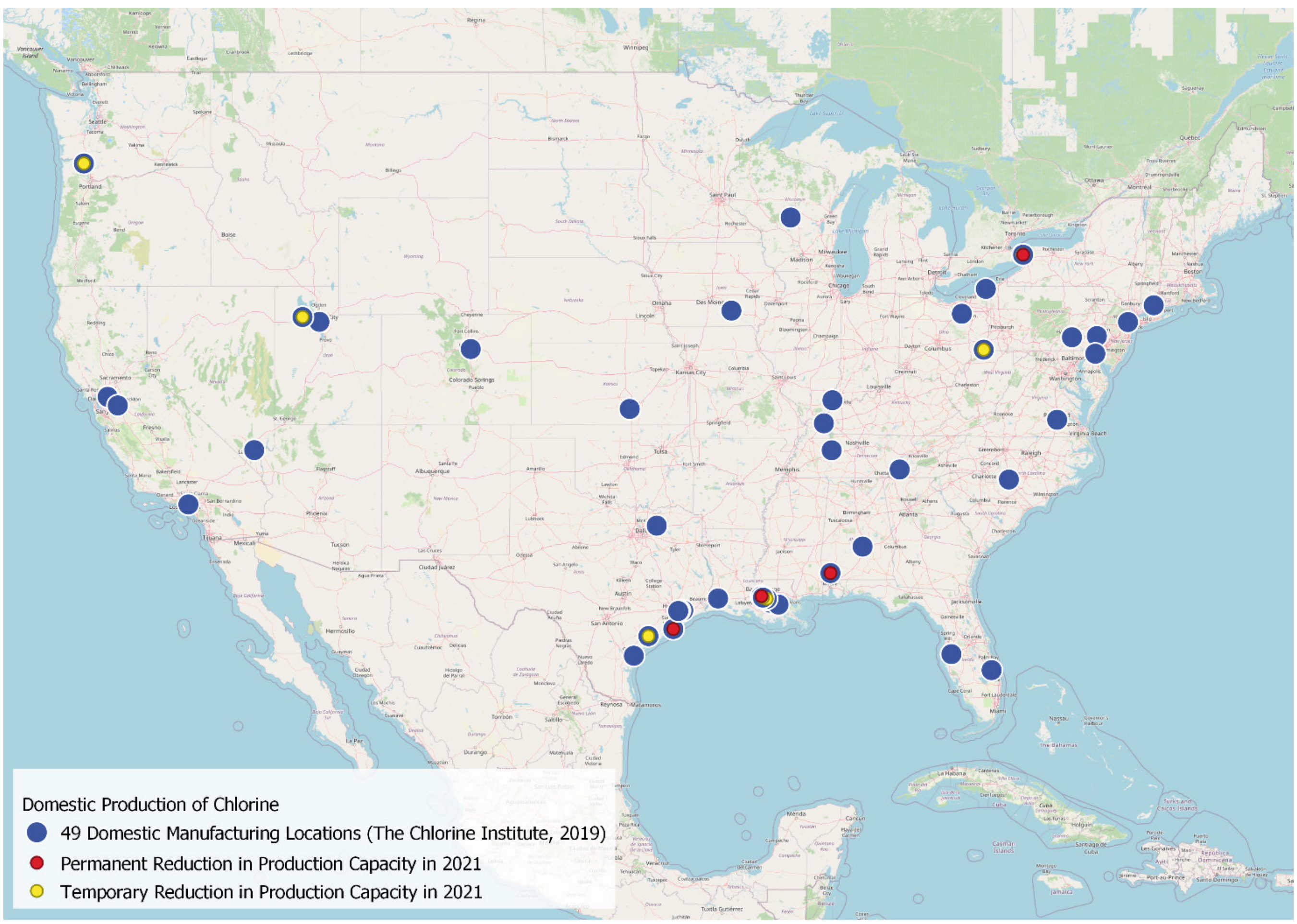


Figure 3-2. Chlor-alkali Production Locations and Sites of Reduced Production Capacity

Reductions in production capacity led many manufacturers to issue force majeure notices to their customers, raise prices above those specified in existing contracts, and place some customers on reduced allocations. Decreased allocations of chlorine and sodium hypochlorite for drinking water and wastewater systems reported to EPA in 2021 occurred in California, Oregon, Washington, Alaska, Utah, Missouri, Ohio, Pennsylvania, New York, Massachusetts, Louisiana, and Florida. Drinking water systems in these states reported that they would issue a boil water notice or shut down if they could not procure the necessary quantities of chlorine or sodium hypochlorite. Wastewater systems risked violation of their permits if they lacked the chemicals needed to disinfect treated effluent prior to discharge.

To address this shortage, the water and chemical sectors worked collaboratively to ensure that available supplies of chlorine and sodium hypochlorite were prioritized for water systems. Additionally, the supply of chlor-alkali chemicals began to improve in the fall of 2021 as equipment issues were resolved and production capacity restored; however, new production challenges occurred in spring of 2022, and widespread reports of price increases continue as of the date of publication of this report.

History of Section 1441 of the Safe Drinking Water Act

There have been repeated shortages of chlor-alkali chemicals that have directly impacted the Water and Wastewater Systems Sector. In 1974, the *New York Times* reported on the potential for an historic shortage of chlorine across the United States. The *Times* reported that large municipal water systems including Philadelphia, Denver, and the Southern California Metropolitan Water District experienced challenges identifying any responsive bidders for chlorine contracts. New York, Detroit, and Chicago all struggled with a very limited chlorine supply, and some municipalities ceased chlorinating wastewater due to lack of supply. At the time, the new requirements of the Clean Water Act for disinfection of treated wastewater, along with increased oversight of industrial facilities, including those manufacturing chlor-alkali products, created a supply/demand imbalance. At the same time, the oil embargo of 1973 led to fuel shortages and sky-high energy prices. The cost of energy, which is significant to the manufacture of chlor-alkali products, greatly impacted costs associated with chlorine production at the time.

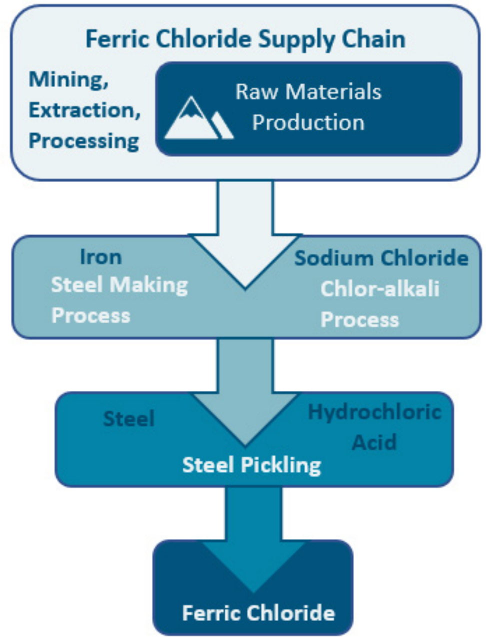
Congressman Paul G. Rogers of Florida, Chairman of the House Subcommittee on Public Health and Environment in 1974, recognized the significance of the chlorine supply shortage for water treatment, and introduced an amendment to the Safe Drinking Water Act (SDWA). To address the pressing concerns of chlorine availability for the water sector at the time, the Safe Drinking Water Act enacted in 1974 was amended to include the following:

> **Safe Drinking Water Act, Section 1441**
> **Assurance of Availability of Adequate Supplies of Chemicals Necessary for Treatment of Water**
> (a) If any person who uses chlorine or other chemical or substance for the purpose of treating water in any public water system or in any public treatment works determines that the amount of such chemical or substance necessary to effectively treat such water is not reasonably available to him or will not be so available to him when required for the effective treatment of such water, such person may apply to the Administrator (of U.S. EPA) for a certification (hereinafter in this section referred to as a "certification of need") that the amount of such chemical or substance which such person requires to effectively treat such water is not reasonably available to him or will not be so available when required for the effective treatment of such water.

The first use of SDWA Section 1441 occurred in June 2021 after EPA developed a process to implement this provision of SDWA in response to the supply challenges that threatened continuity of operations at several water systems. A total of 28 applications from drinking water and wastewater system in nine states were processed between June 2021 and April 2022. Applications were submitted for several chemicals, including: chlorine, sodium hypochlorite, sodium hydroxide, ferric chloride, polymers, sulfur dioxide, liquid oxygen, and carbon dioxide. Though historic instability in some chemical markets had been routine, the level of supply chain disruption ushered in by the COVID-19 pandemic was unprecedented. While the pandemic was one cause of these disruptions, other causes included production interruptions due to natural disasters, equipment failures, planned maintenance, and permanent reductions in production capacity.

Despite the large number of applications received between 2021-2022, as of February 2023 a certification of need has not been issued. Technical assistance from EPA, which has focused on assisting applicants with locating alternative sources of chemical supply combined with outreach to manufacturers and suppliers, has been successful in helping resolve supply shortages.

3.2.2 Ferric Chloride



Ferric chloride is commonly used in drinking water and wastewater treatment as a coagulant. It is estimated that approximately 80% of ferric chloride produced in the United States is used for water treatment, including drinking water as well as municipal and industrial wastewater. In North America, ferric chloride is commonly produced by reacting spent steel pickling liquors with scrap iron and hydrochloric acid to produce ferrous chloride, which is then reacted with chlorine in an oxygen-rich environment to generate ferric chloride. Under normal conditions, these precursors are readily available.

However, the disruption in chlor-alkali production that begin in the fall of 2020 and continued through 2021 resulted in disruptions in the supply of chlorine and hydrochloric acid (see **Section 3.2.1**). Concurrently, there was also a contraction in domestic steel production, which reduced availability of spent steel pickling liquors. Discussion with industry representatives indicated that challenges in obtaining ferric chloride were primarily due to a shortage of hydrochloric acid and spent pickling liquor. In addition to the shortage of precursors, there was also a series of equipment failures at a major ferric chloride production facility, and due to the specialized nature of the equipment, it took months to complete the repairs and restore facility operations There were also reports of truck and driver shortages impacting all parts of the supply chain. Additionally, rail lines were temporarily blocked in the western United States due to wildfires, forcing reroutes that delayed deliveries by several weeks.

These conditions resulted in a situation in which the total available supply of ferric chloride was insufficient to meet water sector demand. Because the water sector is the primary consumer of ferric chloride, there was insufficient inventory in the supply that would allow for reprioritization of available ferric chloride to the water sector. Thus, impacted water systems had to work with their suppliers and state primacy agencies to evaluate other coagulants that could be used until the supply of ferric chloride recovered.

Causes of Supply Chain Disruptions: Changing Business Models

Various business disruptors, most recently the supply chain disruptions associated with the COVID-19 pandemic, have led many businesses to reevaluate reliance on complex global supply chains. Supply chains built for maximum efficiency may be found to introduce vulnerabilities such as overreliance on imports through transportation modes that have disruptions and unpredictable costs. A move towards more resilient supply chains could result in an expansion of domestic production capacity.

3.2.3 Carbon Dioxide

Gaseous carbon dioxide, stored as a cryogenic liquid, is used in both water treatment and wastewater treatment for pH control. Much of the carbon dioxide sold in the commercial market is recovered as a byproduct of ethanol, ammonia, and hydrogen production. Historically, the ethanol industry has produced more than half of the carbon dioxide sold on the commercial market. The majority of carbon dioxide produced for the commercial market is consumed by the food and beverage industry. The market for water treatment is significantly smaller.

Between 2017 and 2021 numerous water providers received force majeure notices from their contracted carbon dioxide suppliers. In instances where a reason was offered for the notice, most suppliers referred to a lack of feedstock (ethanol) due to temporary shutdown of ethanol production facilities. The fluctuation in demand for ethanol due to fluctuating demand for refined petroleum products has directly affected the availability of refined carbon dioxide. Carbon dioxide production can fluctuate seasonally as well, as it may be tied to corn harvest (ethanol) and fertilizer production (ammonia). Both industries have planned downtimes for annual maintenance.

The COVID-19 pandemic created significant volatility in the commercial market for carbon dioxide. In an April 2020 letter to the White House Coronavirus Task Force, the Compressed Gas Association and other stakeholders expressed great concern regarding "a significant risk of a shortage in carbon dioxide that would significantly impact access to essential food and beverage supplies and other essential sectors of the U.S. economy" due to the ongoing pandemic (Compressed Gas Association, 2020). The idling of ethanol and ammonia production plants, both primary sources of carbon dioxide raw, greatly reduced the domestic supply of purified carbon dioxide. On April 20, 2020, Advanced Biofuels USA reported that 34 of the 45 U.S. ethanol plants had paused operations. A confluence of events reduced demand for ethanol and ammonia-based fertilizer, and the supply of purified carbon dioxide for the commercial market dramatically decreased (Advanced Biofuels USA, 2020). Certain areas of the U.S. were more heavily impacted by the volatile carbon dioxide market conditions in 2020. As shown in **Figure 3-3**, the northeast, southeast, and southwest were all impacted by closures or idling of regional carbon dioxide purification plants from 2020 to 2021. Water systems in Florida are uniquely vulnerable to disruptions in the supply of carbon dioxide given that there is only one producer in the region – in southern Georgia. When that production facility permanently closed in 2020 (Voegele, 2020), the supply of carbon dioxide to water systems in Florida was severely limited.

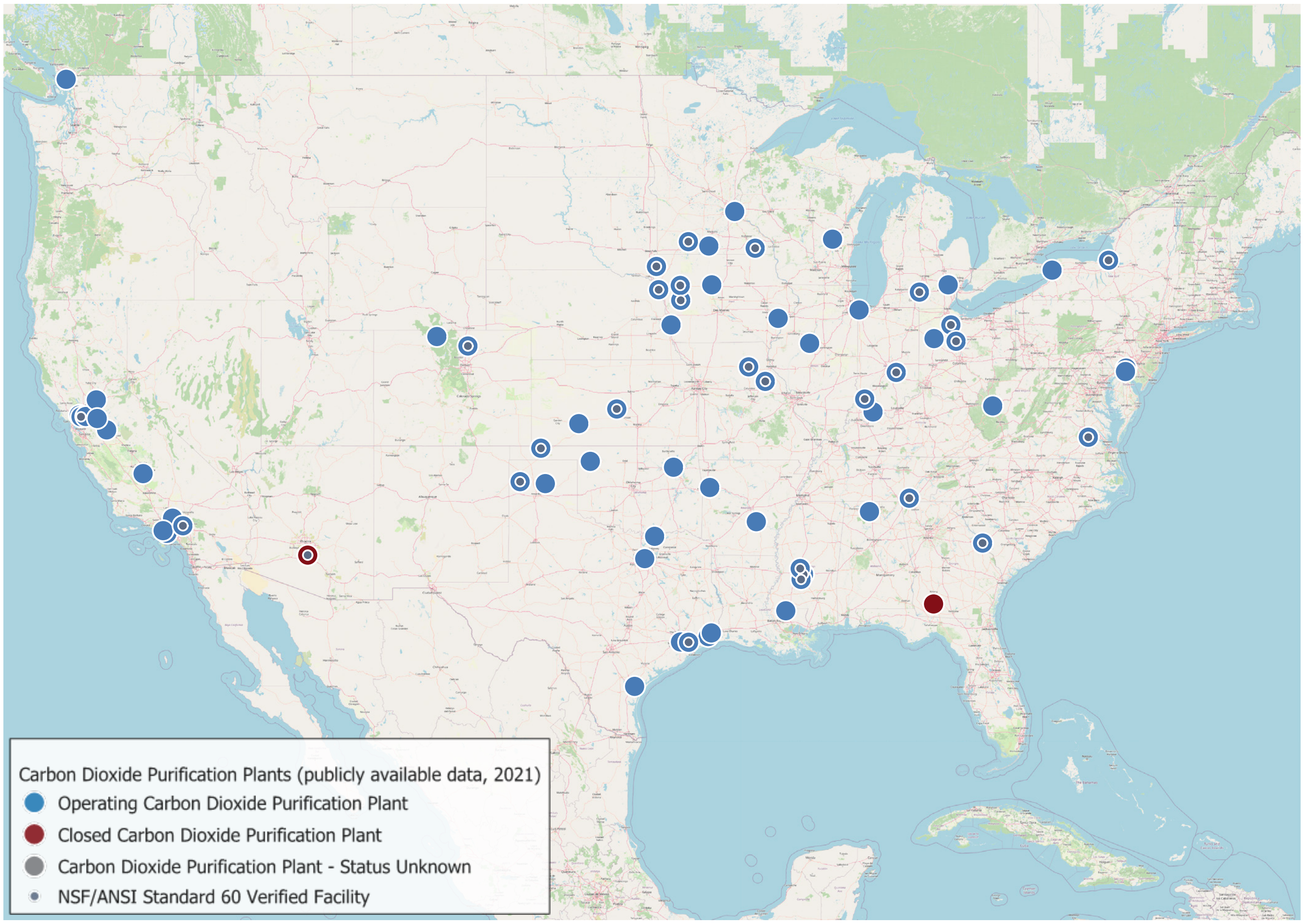


Figure 3-3. Status (2021) of Domestic Carbon Dioxide Purification Plants

The period of 2020 to 2021 represented a true shortage, where the total regional supply of carbon dioxide was insufficient to meet water sector demand in Florida. However, most water systems were able to obtain a supply at a substantially higher cost, which was generally attributed to increased transportation costs as suppliers brought in product from distant purification plants to meet the demand of their water system customers. Given that food and beverage grade carbon dioxide is more widely available than NSF/ANSI Standard 60 certified carbon dioxide, several water systems worked with their state drinking water primacy agency to allow for use of food or beverage grade carbon dioxide until the supply of NSF/ANSI Standard 60 certified carbon dioxide was restored. Some states have codified use of food or beverage grade carbon dioxide for drinking water treatment into law. For example, in Florida, the regulations allow the use of chemicals certified in the standards in Food Chemicals Codex per F.A.C. 62-555-350(3)(a).

Carbon Dioxide Grading for Water Treatment

The purification specifications for carbon dioxide are driven in large part by the food and beverage industry, the primary consumer markets. The standards that govern the quality of carbon dioxide used by the largest customer base are established by the Compressed Gas Association, and not all carbon dioxide on the commercial market is NSF/ANSI Standard 60 certified.

3.2.4 Liquid Oxygen (LOX)

Oxygen, provided in bulk as LOX, is used directly in drinking water treatment to generate ozone for use as a primary disinfectant and strong oxidant, and in wastewater treatment for aeration and oxidation. Oxygen may also be used directly or indirectly in the production of water treatment chemicals including ferric chloride, ferric sulfate, potassium permanganate, sulfur dioxide, and sulfuric acid. The commercial market for LOX relies on centralized production at facilities equipped with large air separation units and purification processes needed to remove impurities and meet a variety of standards and the infrastructure and logistics to move the LOX to where it is needed. Most cryogenic air separation facilities produce LOX at greater than 99% purity to cover a broad range of applications, including industrial applications such as steel and other metals manufacturing, petrochemical manufacturing, and the space industry (Cockerill, 2021; Parkinson, 2021). Highly purified LOX is in high demand by several industries, including the healthcare and food and beverage industries. The overall water sector market for LOX is estimated at less than 5% of total U.S. consumption. As pictured in **Figure 3-4**, while there are an appreciable number of LOX production facilities throughout the geographic area shown in the figure, there are only three production facilities in Florida and roughly half a dozen in nearby states that might serve the Florida market.

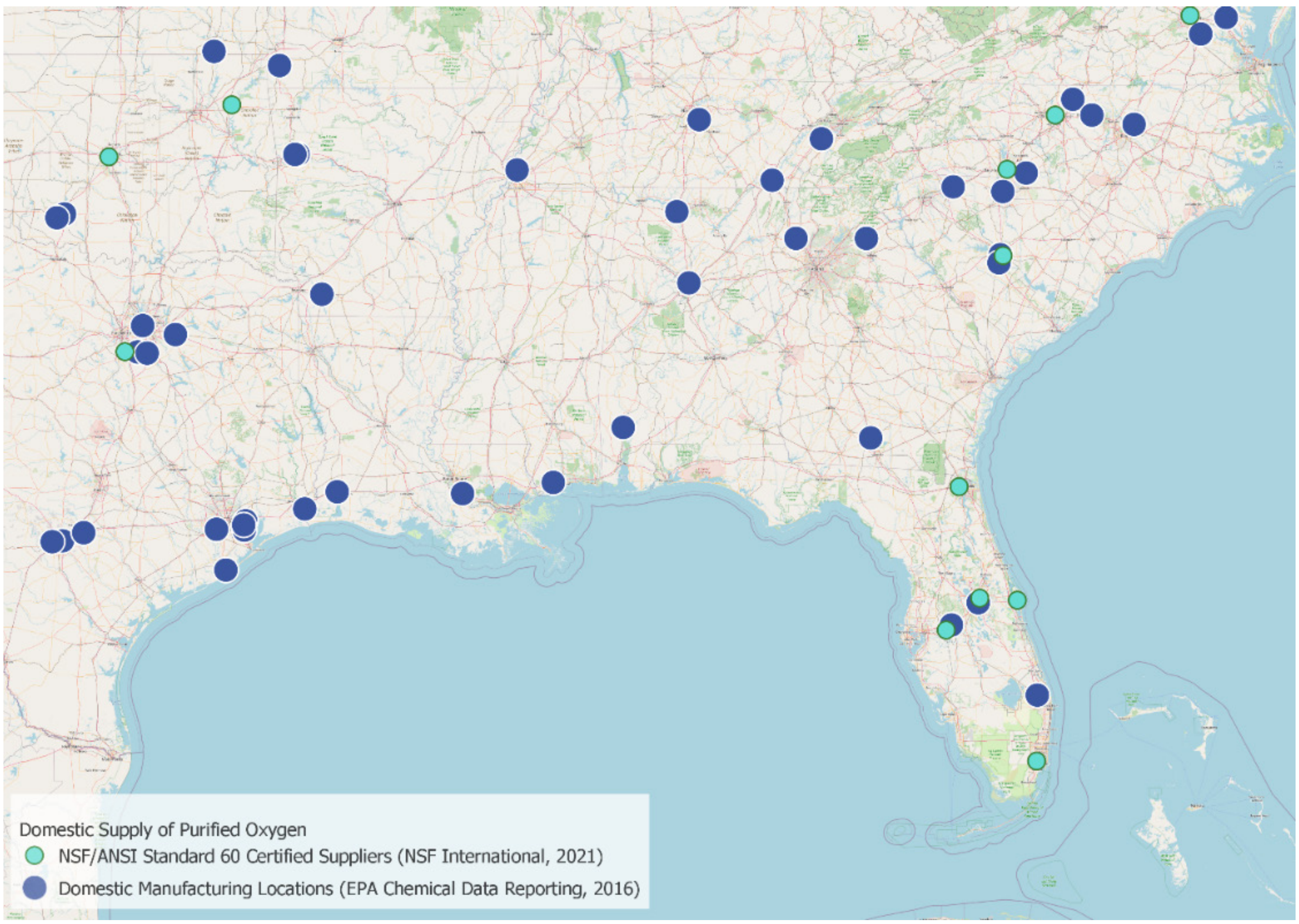


Figure 3-4. Domestic Supply of Purified Oxygen in the Southeastern U.S.

The availability of LOX for medical treatment during the COVID-19 pandemic was a persistent concern, particularly with the adoption of high-volume oxygen therapy as standard treatment for hospitalized COVID-19 patients. In the summer of 2021, COVID-19 hospitalizations, and the accompanying demand for LOX in healthcare settings, soared. During this same period, several LOX suppliers issued force majeure notices to industrial customers, which included drinking water and wastewater systems. In extreme cases, water system customers were placed on zero allocation for an unspecified duration. Force majeure notices were also issued to water treatment chemicals producers which require LOX to manufacture chemicals such as ferric sulfate.

The two primary reasons cited in force majeure notices were the increased demand for LOX in healthcare settings for COVID-19 patients, as well as a lack of commercial drivers with a Hazardous Materials Endorsement (HME) and experience offloading LOX. The increase in demand due to dramatic regional increases in COVID-19 hospitalizations coupled with insufficient transportation resources resulted in a severe regional shortage. Similar to the situation with carbon dioxide discussed in the previous section, water systems in Florida faced unique challenges in securing adequate supplies of LOX. This was not only due to the limited number of producers and suppliers that serve the Florida market, but also the extraordinarily high number of COVID-19 hospitalizations and high demand for medical use of LOX in the state.

Given that another critical infrastructure, healthcare, was competing for the available supply of LOX, it was not feasible to divert LOX from hospitals to water treatment facilities. To address this issue, the water sector and chemical sector collaborated to notify LOX suppliers of the criticality of water sector customers that depend on LOX for ozone generation and subsequent water disinfection. Additionally, some water systems were able to exercise operational flexibilities, such as feeding chlorine or sodium hypochlorite to meet disinfection requirements, switching to another source that doesn't require disinfection with ozone, or issuing conservation orders to stretch available LOX supplies. It was observed that LOX suppliers coordinated with their water system customers to ensure that critical needs were met. For example, water systems that had the operational flexibility to forego use of ozonation for a limited time might have been placed on zero allocation of LOX, while systems that depended on ozonation to meet disinfection requirements were provided with full or partial allocation depending on their stated needs. Fortunately, the COVID-19 spike in the summer of 2021 subsided and the equilibrium between supply of and demand for LOX was reestablished.

Oxygen Grading for Water Treatment

The specifications for highly purified LOX are driven in large part by the standards required by the sector with the largest demand. High-volume end uses such as medical applications and food packaging are certified by a variety of organizations including the U.S. Food and Drug Administration, Compressed Gas Association, International Organization for Standardization (ISO), and Food Chemicals Codex standards. Most commercial air separation plants have on-site testing for quality assurance to ensure that batches meet the intended specifications. These industry standards may be different from those required for drinking water applications, and not all air separation plants have been certified under NSF/ANSI Standard 60.

3.2.5 Phosphate Rock

Phosphate rock is a raw material necessary for production of phosphate-based corrosion control chemicals and water fluoridation chemicals. While the U.S. is a leading worldwide producer of phosphate rock and phosphoric acid, approximately 95% of domestically produced phosphate rock / phosphoric acid is used in captive manufacturing to produce fertilizer (USGS, 2020). Domestic production of phosphate-based chemicals other than fertilizer may rely on import of phosphate rock from a small number of countries including Morocco, China, Peru, and Russia. Domestic manufacturers and suppliers of phosphate-based water treatment chemicals oftentimes rely on the international market for supply of raw materials. Price and access on the international market, like the domestic market, is driven by agricultural demand and increasingly by demand for lithium iron phosphate battery materials (Spears et al., 2022). The international market for phosphate rock and phosphoric acid may also be impacted by trade barriers, international events such as armed conflict, and natural disasters. This finding is reinforced in a 2019 study by Nedelciu et al. (2020), which assessed that the global phosphate supply chain is challenging to analyze in part due to a lack of global reporting, particularly as it relates to market dynamics, and access and availability of phosphate rock resources.

Water producers have repeatedly experienced short-term disruptions in the supply of water fluoridation chemical. Disruptions to phosphoric acid production and the supply chain for phosphate rock can have a significant impact on availability of fluoridation chemicals. Much of the domestic fluoridation chemical supply is produced as a byproduct of fertilizer production in a geographically concentrated area (i.e., Florida and Louisiana), which may be impacted by natural disasters and planned maintenance periods. Manufacturers and suppliers of other phosphate-based chemicals such as orthophosphates and polyphosphates may encounter persistent challenges in obtaining phosphate rock, phosphoric acid, or downstream precursor chemicals such as monosodium phosphate on the international market. This has led to repeated shortages of phosphate-based water treatment chemicals. Between 2020 and 2022, the disruptions in international trade caused by the COVID-19 pandemic severely challenged these manufacturers.

Availability and price increases of phosphate-based corrosion inhibitors can be a challenge considering Lead and Copper Rule requirements. For example, Slabaugh et al. (2015) discussed potential improvements in sampling as leading to increased use of phosphate-based corrosion inhibitors. Furthermore, the authors indicated that given historically-documented price increases of approximately 233% during the Great Recession (Henderson et al. 2009), they anticipated the potential for future significant price increases and availability challenges.

Causes of Supply Chain Disruptions: International Trade Policies

Trade policies are often used as a tool to maintain good international relationships or as punitive measures to address disagreements between trading partners. Between 2018 and 2022, domestic trade policies have been adjusted to address trade disputes with China and Russia's invasion of Ukraine. Trade disputes can impact the market for exports but can also impact the price and availability of imports required for chemical manufacturing. If the trade partner is a crucial source of a raw material, supply of the raw material may be heavily impacted.

China is a vital trading partner for the chemical industry. Starting in 2018, the United States imposed a series of tariffs on import of Chinese goods, including a multitude of chemicals. A significant increase in tariffs on many chemicals resulted in a subsequent shift in import dynamics where possible. Tariffs imposed on chemical imports from China have resulted in improved supply chain resilience in situations where manufacturers were able to pivot and import from other countries. In other instances, alternative sources for the required chemicals have not been feasible, and the tariff has resulted in higher prices or market instability for domestic products.

In spring of 2022 the U.S. and the European Union placed sanctions on Russia in response to Russia's invasion of Ukraine. Though fertilizers are exempt from these sanctions, prices for nitrogen- and phosphorous-based fertilizer, of which Russia is a significant exporter, increased worldwide in the wake of implementation of the sanctions. While other countries look to fill the gap and supply fertilizer, higher prices and a tighter market have placed pressure on the supply of phosphate rock, potash, ammonia, and phosphoric acid. While the impact of these trade policies is still unfolding as of the writing of this report, there is some expectation that competition on the international market may limit availability of these resources.

3.2.6 Potassium Permanganate

Potassium permanganate, and to a lesser extent sodium permanganate, are used as oxidants in drinking water and wastewater treatment (AWWA, 2016). Common applications include iron and manganese removal, hydrogen sulfide removal, taste and odor compound removal, arsenic removal, and control of nuisance organisms such as zebra mussels. Municipal and industrial water treatment applications account for more than 50% of domestic consumption.

Domestic production capacity exceeds domestic consumption needs, and in 2019, approximately 27% of domestic production was exported. Imports, almost exclusively from India, supplied approximately 11% of domestic consumption in that same year. One company, Carus LLC, is the only domestic manufacturer of potassium permanganate in North America.

On January 11, 2023, a fire broke out at the Carus LLC facility in LaSalle, IL, severely damaging the only potassium permanganate production facility in the U.S. This prompted Carus LLC to issue a force majeure notice stating that orders may not be filled within a 90-day period (Mullin, 2023). Carus and other water treatment chemical suppliers turned to imports from India and China. However, at the time of this report, it was unclear whether India had adequate capacity to make up for the lost production from the damaged Carus LLC facility, and imports from China are stymied by anti-dumping regulations, imposing a 130% effective tariff on imports from China (Federal Register, 2021).

This case study demonstrates how the combined vulnerabilities of a highly concentrated domestic production base combined with trade policies that impede import from one of the largest world producers can present significant risk to the domestic supply of water treatment chemicals.

3.3 Risk of Water Treatment Chemical Supply Disruption

While the previous section presented several case studies of supply disruptions that have occurred, this section considers the potential for future water treatment chemical supply disruptions. The 46 chemicals, including 35 direct use water treatment chemicals along with 11 precursors and raw materials were evaluated to assess their relative risk of a supply disruption. The relative risk analysis was conducted according to the methodology described in **Section 2.3**, which was developed using insights gained from evaluation of real-world supply disruptions, such as those described in **Section 3.2**, and an understanding of the conditions that lead to supply disruptions as described in **Section 3.1**. The following four subsections discuss the relative risk as well as the ratings for the three risk parameters.

3.3.1 Relative Risk

A summary of the relative risk evaluation results for the 46 chemicals considered in this study is presented in **Table** 3-2. This table shows that most chemicals were assessed as low or moderate-low risk for supply chain disruptions (23 and 17 of 46 chemicals, respectively). While there were no chemicals with a as high risk rating, six chemicals were assessed to be at moderate-high risk of future supply chain disruption.

Table 3-2. Risk Rating Summary for 46 Chemicals Important to Water Treatment

Chemical Name	Risk Rating	Criticality	Likelihood	Vulnerability
Acrylamide*	ML	H	ML	L
Aluminum Hydroxide*	ML	H	L	MH
Aluminum Sulfate	L	H	L	MH
Ammonium Hydroxide	L	H	L	L
Anhydrous Ammonia	L	H	L	L
Bauxite*	ML	H	L	MH
Calcium Carbonate	L	H	L	L
Calcium Hydroxide	L	H	L	L
Calcium Hypochlorite	L	MH	L	ML
Calcium Oxide	L	H	L	L
Carbon Dioxide	ML	H	H	L
Chlorine	MH	H	H	L
Citric Acid	ML	H	ML	ML
Diallyldimethylammonium chloride (DADMAC)*	MH	H	ML	MH
Disodium Phosphate	MH	H	ML	MH
Ferric Chloride	ML	H	H	L
Ferric Sulfate	ML	H	ML	L
Ferrous Chloride	ML	H	H	L
Ferrous Sulfate	L	H	L	L
Fluorosilicic Acid	ML	L	H	MH
Hydrochloric Acid	ML	H	H	L
Hydrogen Peroxide	L	H	L	L
Ilmenite*	L	MH	L	ML
Manganese Ore*	L	H	L	MH
Monosodium Phosphate	ML	H	ML	MH
Oxygen	ML	H	H	L
Phosphate Rock*	ML	H	H	L
Phosphoric Acid	MH	H	H	L
Polyaluminum Chloride	ML	H	L	MH
Potassium Chloride*	L	MH	L	MH

Chemical Name	Risk Rating	Criticality	Likelihood	Vulnerability
Potassium Hydroxide	L	ML	L	MH
Potassium Permanganate	L	H	L	MH
Silica	L	H	L	L
Sodium Carbonate	ML	H	L	ML
Sodium Chlorate*	L	MH	L	MH
Sodium Chloride	L	H	L	L
Sodium Chlorite	L	MH	L	MH
Sodium Hydroxide	MH	H	H	L
Sodium Hypochlorite	MH	H	H	L
Sodium Salts of Polyphosphates	ML	H	ML	MH
Sodium Silicate	L	H	L	ML
Sulfur Dioxide	ML	H	H	L
Sulfur*	L	H	L	L
Sulfuric Acid	L	H	L	L
Zinc Orthophosphate	L	H	ML	L
Zinc*	L	H	L	L

H High Risk MH Moderate-High Risk ML Moderate-Low Risk L Low Risk

*Denotes raw material or precursor chemical with no direct-use water treatment application

The six chemicals assessed to be at moderate-high risk are: chlorine, sodium hypochlorite, disodium phosphate, phosphoric acid, sodium hydroxide, and DADMAC. All six of these chemicals have both direct use and precursor applications, and four of the six have experienced supply chain disruptions between 2000 and 2022. The criticality of all six chemicals was rated as high, and the likelihood of four of the six chemicals was also rated high. However, vulnerability was rated as low for four of the six chemicals, including chlorine and sodium hypochlorite.

It is notable that three chlor-alkali chemicals (chlorine, sodium hydroxide, and sodium hypochlorite) account for half of the chemicals in this moderate-high risk category. This result warrants attention given the importance of these chemicals to water treatment as direct-use treatment chemicals and the use of chlorine and sodium hydroxide as precursors to the manufacture of numerous other water treatment chemicals.

Two phosphate rock derivative chemicals (disodium phosphate and phosphoric acid) are present in the moderate-high risk category. This finding is partially attributable to the dependence of these two chemicals on availability of phosphate rock, which is the raw material deemed at greatest risk of experiencing future supply disruptions. As discussed in Section 3.2.5, there are specific vulnerabilities to the supply chain for phosphate rock. These vulnerabilities, as applicable to disodium phosphate and phosphoric acid, are further discussed in Section 3.3.4.

Five of the six chemicals in the moderate-high risk category are derivative products of two chemical families: sodium chloride and phosphate rock. The family trees for these raw materials are featured in **Figure 3-6** and **Figure 3-7**. Combined, water treatment chemicals requiring one or both of these foundational inputs account for 54% of the direct-use chemicals considered in this study.

Section 3.3.2 through **Section 3.3.4** discuss the ratings for criticality, likelihood, and vulnerability, providing insight into the drivers for the relative risk ratings for the 46 chemicals studied.

3.3.2 Criticality

Evaluation of the criticality of each chemical considered whether use of the chemical for water treatment is necessary or discretionary, extent of use in water treatment, and use as a precursor in the manufacture of other water treatment chemicals.

As shown in **Figure 3-5** approximately 85% (39 of the 46 chemicals profiled) were assessed to have a criticality rating that placed them in the high range, reflecting the study focus on chemicals that are essential to producing safe drinking water for the public. Chlorine is one such chemical which was assessed in the high range based on its widespread use in a critical treatment process (disinfection) along with use of chlorine in the production of other water treatment chemicals (hydrochloric acid, ferrous and ferric chloride, ferric sulfate, sodium hypochlorite, and calcium hypochlorite). The criticality rating for ilmenite, a raw material which can be used to produce the ferrous/ferric chloride and ferrous/ferric sulfate was assessed in the moderate-low range because its use as a raw material in the production of iron-based coagulants in North America is uncommon compared to iron oxide (IDEM, 2016). Fluorosilicic acid was assessed in the low range based on its use in a non-critical water treatment process (fluoridation) that is not required for compliance with federal drinking water regulations. Furthermore, fluorosilicic acid is not used as a precursor in the production of other water treatment chemicals.

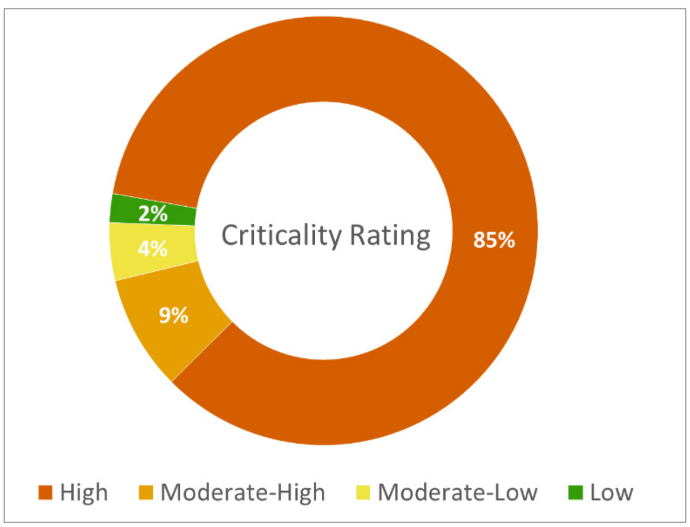
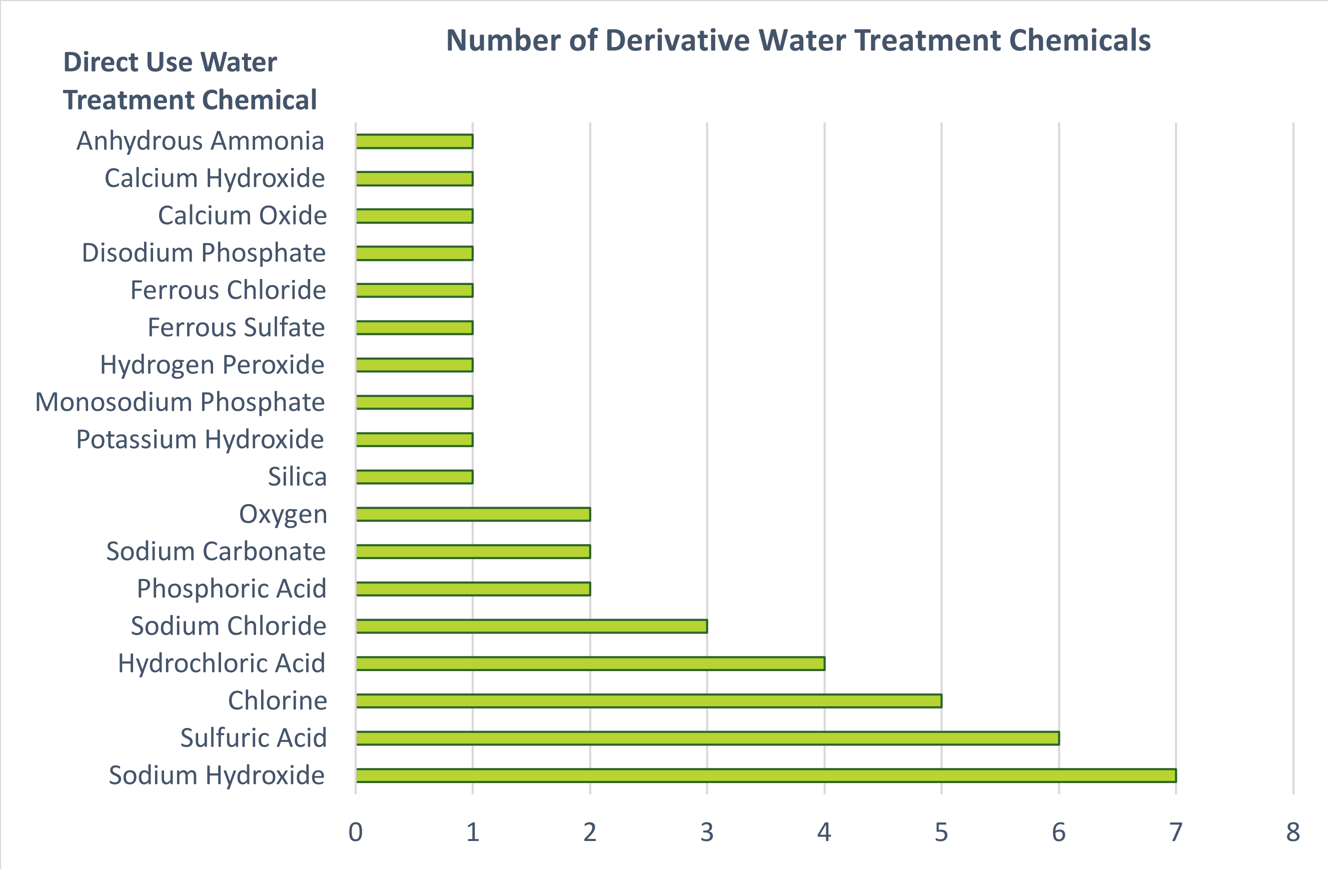


Figure 3-5. Criticality Rating for 46 Chemicals Important to Water Treatment

Chemicals that have both a direct use application and serve as precursors to the production of other water treatment chemicals have the highest criticality rating. A list of these direct use treatment chemicals is presented in **Figure 3-6**, along with the number of derivative water treatment chemicals, identified in this study, that rely on the listed chemical for production. As an example, sulfuric acid is directly used in water treatment for pH control but is also used in production of eight other direct-use water treatment chemicals, such as phosphoric acid, ferrous sulfate, and ferric sulfate. The chlor-alkali chemicals sodium hydroxide and chlorine are precursors to eight and five direct use chemicals, respectively.

Figure 3-6. Number of Derivative Water Treatment Chemicals Manufactured with the Listed Direct-Use Chemicals



The criticality of chlor-alkali chemicals to the water sector is further illustrated in **Figure 3-7**, which shows the primary chlor-alkali products and their derivative water treatment chemicals, all of which derive from sodium chloride. In total, sodium chloride derivatives account for 26% (9 out of 35 chemicals) of the direct-use water treatment chemicals assessed in this study.

Similarly, phosphoric acid and sulfuric acid are important to the water sector both as direct use chemicals and as precursors to the manufacture of other water treatment chemicals. These chemicals derive from two minerals, phosphate rock and sulfur, and the chemicals important to the water sector that are manufactured from these two minerals are depicted in **Figure 3-8**. In total, phosphate and sulfur derivatives account for 29% (10 out of 35 chemicals) of the direct-use water treatment chemicals assessed in this study.

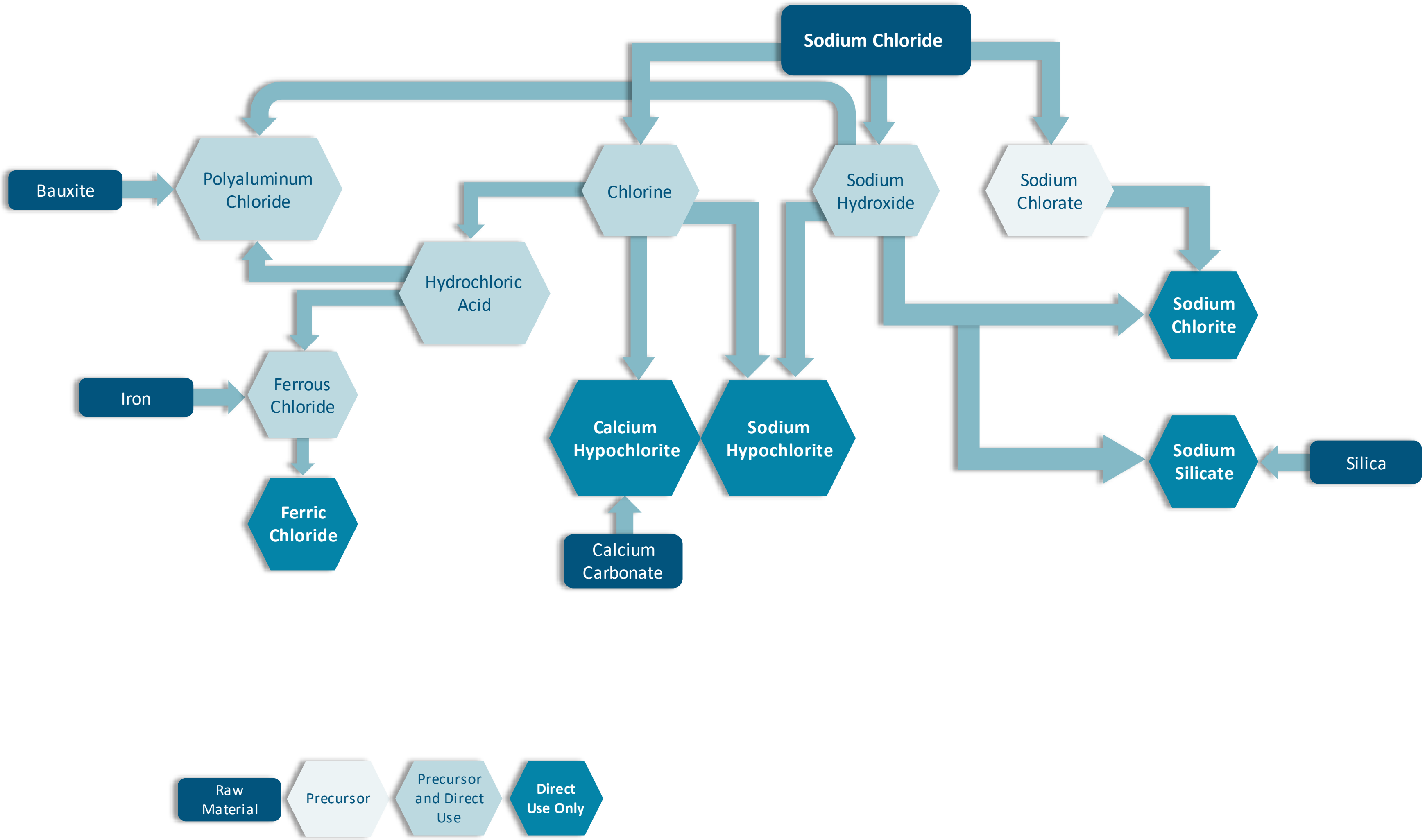


Figure 3-7. Water Treatment Chemicals and Precursors Derived from Sodium Chloride

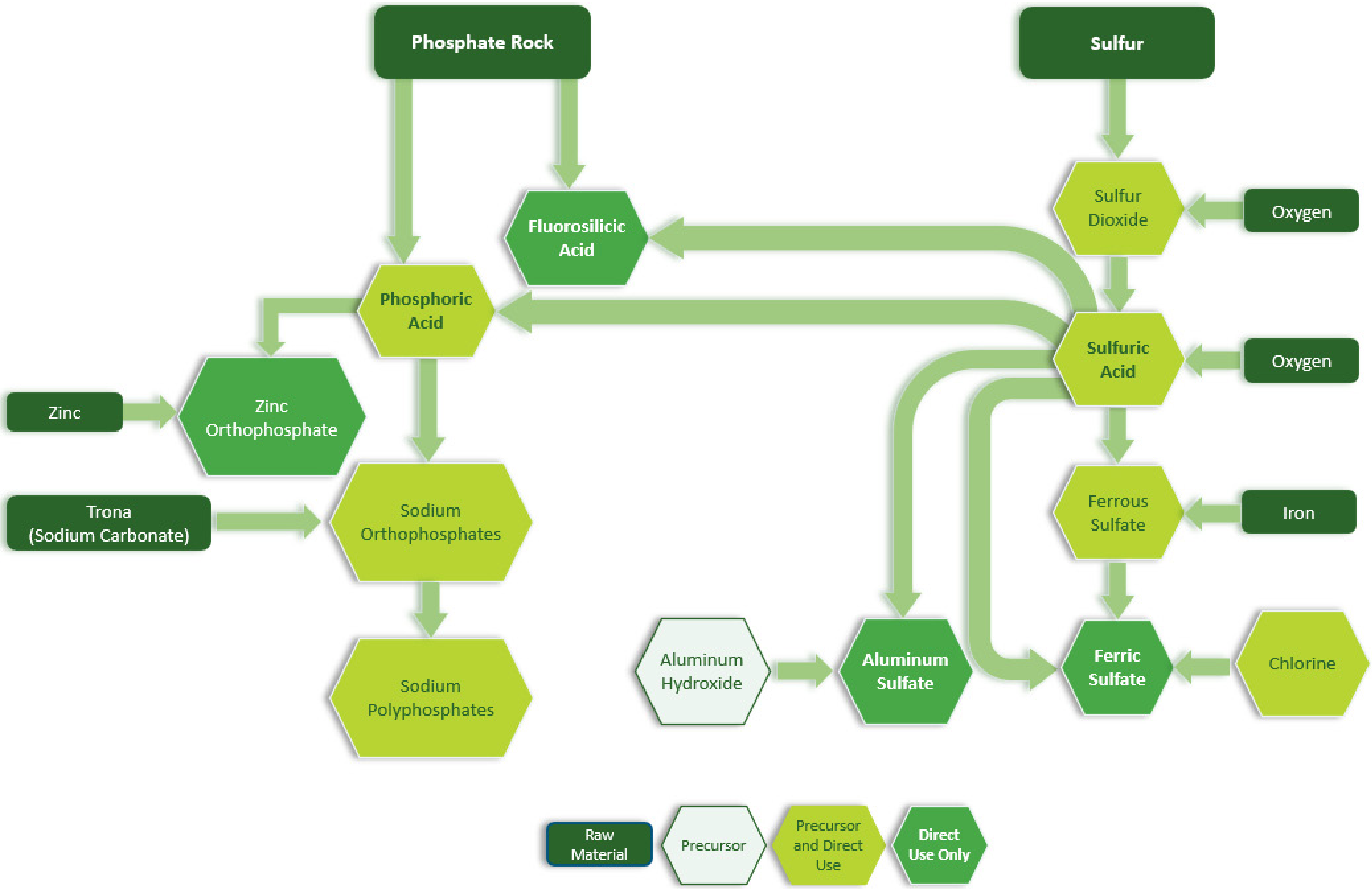


Figure 3-8. Water Treatment Chemicals and Precursors Derived from Phosphate Rock and Sulfur

3.3.3 Likelihood

Evaluation of the likelihood of a supply disruption for each chemical was based on the historic record of supply chain disruptions between 2000 and 2022, as described in **Section 2.3.2**. A summary of the likelihood ratings is presented in **Figure 3-9.** The likelihood rating was assessed as high for 12 chemicals (26%), moderate-high for eight chemicals (17%), and low for 26 chemicals (57%). Chemicals with a high likelihood rating have a history of either widespread or regional domestic shortages. It is noteworthy that phosphate rock is included in this group. Though the U.S. is a leading worldwide producer of phosphate rock, historically approximately 95% of domestically mined phosphate is used in captive production of fertilizer (USGS, 2017). Thus, at times water treatment chemical producers must rely on imported sources of phosphate rock or phosphate precursor chemicals for water treatment chemical production. This dynamic has created supply chain disruptions specific to production of phosphate-based water treatment chemicals, including corrosion inhibitors and water fluoridation chemicals.

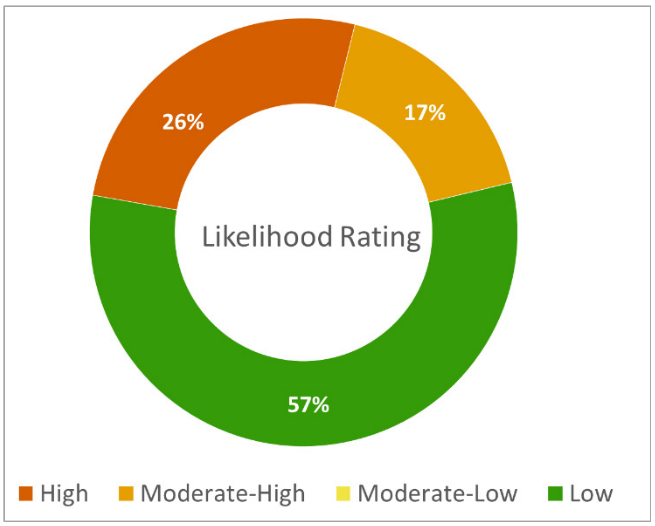


Figure 3-9. Likelihood Ratings for the 46 Chemicals Important to Water Treatment

Figure 3-10 illustrates the distribution of 46 chemical researched under this study across the five categories of historic supply disruptions. Overall, 59% of chemicals were found to have experienced at least one supply chain issue between 2000 and 2022. Three (7%) water treatment chemicals have a history of widespread shortages, while nine (20%) precursor and water treatment chemicals have a history of regional shortages. Two out of three of the water treatment chemicals with a significant history of widespread shortage are chemicals produced in the chlor-alkali industry, while the third, fluorosilicic acid, is a byproduct of domestic fertilizer production.

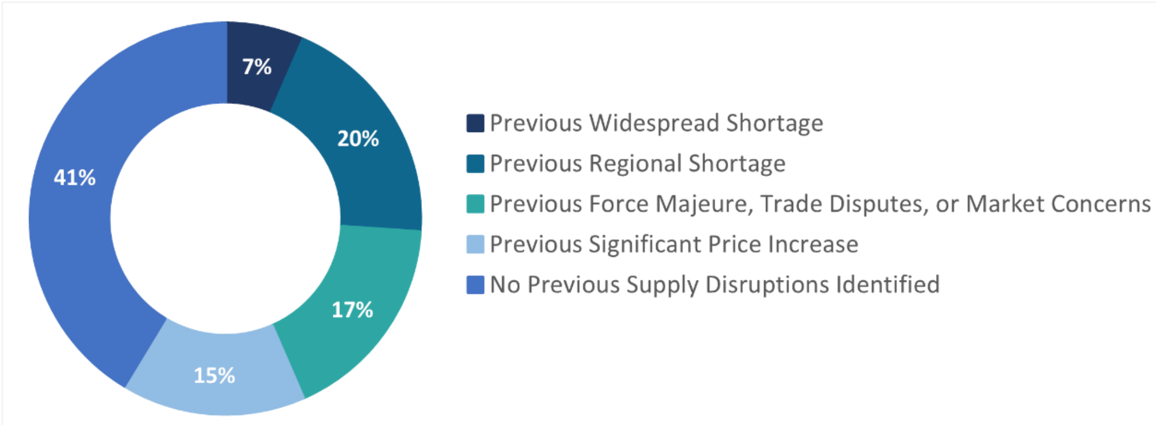


Figure 3-10. History of Supply Chain Disruptions (2000-2022) for 46 Chemicals Important to Water Treatment

3.3.4 Vulnerability

Evaluation of the vulnerability of each chemical to conditions that can result in supply disruptions was based on the following:

- Domestic production capacity relative to domestic consumption, without differentiating between captive consumption and merchant market consumption
- Percentage of domestic consumption dependent on imports
- Barriers to international trade
- Competition for the chemical from other markets
- Shelf-life of the chemical

As show in **Figure 3-11** approximately 32% (15) of the researched chemicals have a vulnerability rating that places them in the moderate-high range. Two phosphate-based compounds (disodium phosphate and sodium polyphosphates) have a vulnerability rated as moderate-high based on limited known domestic production facilities, a highly competitive domestic market, short shelf life, and high tariffs on imports from the current leading worldwide exporter (China). Citric acid, which has a vulnerability rated as moderate-low, has limited known domestic manufacturing locations with significant competing markets, however, as of the writing of this report there was significant domestic production. Chlorine and sodium hypochlorite were rated as low vulnerability based on widespread domestic manufacturing capabilities and a robust domestic manufacturing base. However, the permenant reductions in chlor-alkali production capacity that occurred in 2021, and the potential for future reductions, could make chlor-alkali chemicals and their derivatives more vulnerable to future supply disruptions.

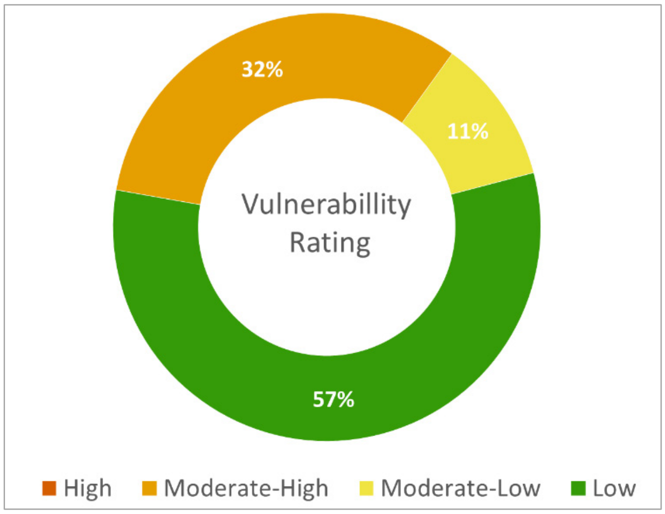


Figure 3-11. Vulnerability Rating for 46 Chemicals Important to Water Treatment

Evaluation of a chemical's vulnerability to supply disruptions included an analysis of dependence on imports to meet domestic consumption. Although the U.S. is a leading worldwide producer of many of the chemicals evaluated, U.S. manufacturers and suppliers of water treatment chemicals rely on imports for many precursors and raw materials. Dependence on imports was incorporated into the vulnerability rating through a review of trade, production, and domestic consumption data. **Figure 3-12** shows the U.S. dependence on imports, in 2019, for 10 raw materials essential to the production of water treatment chemicals. The U.S. is nearly 100% dependent on imports of manganese ore, one of the raw materials necessary for production of potassium permanganate, and 72% of the manganese ore imported to the U.S. comes from one source, Gabon. The U.S. is also highly dependent on imports of bauxite, which is the source of aluminum for all aluminum-based coagulants, and 65% of bauxite imports originate from Jamaica.

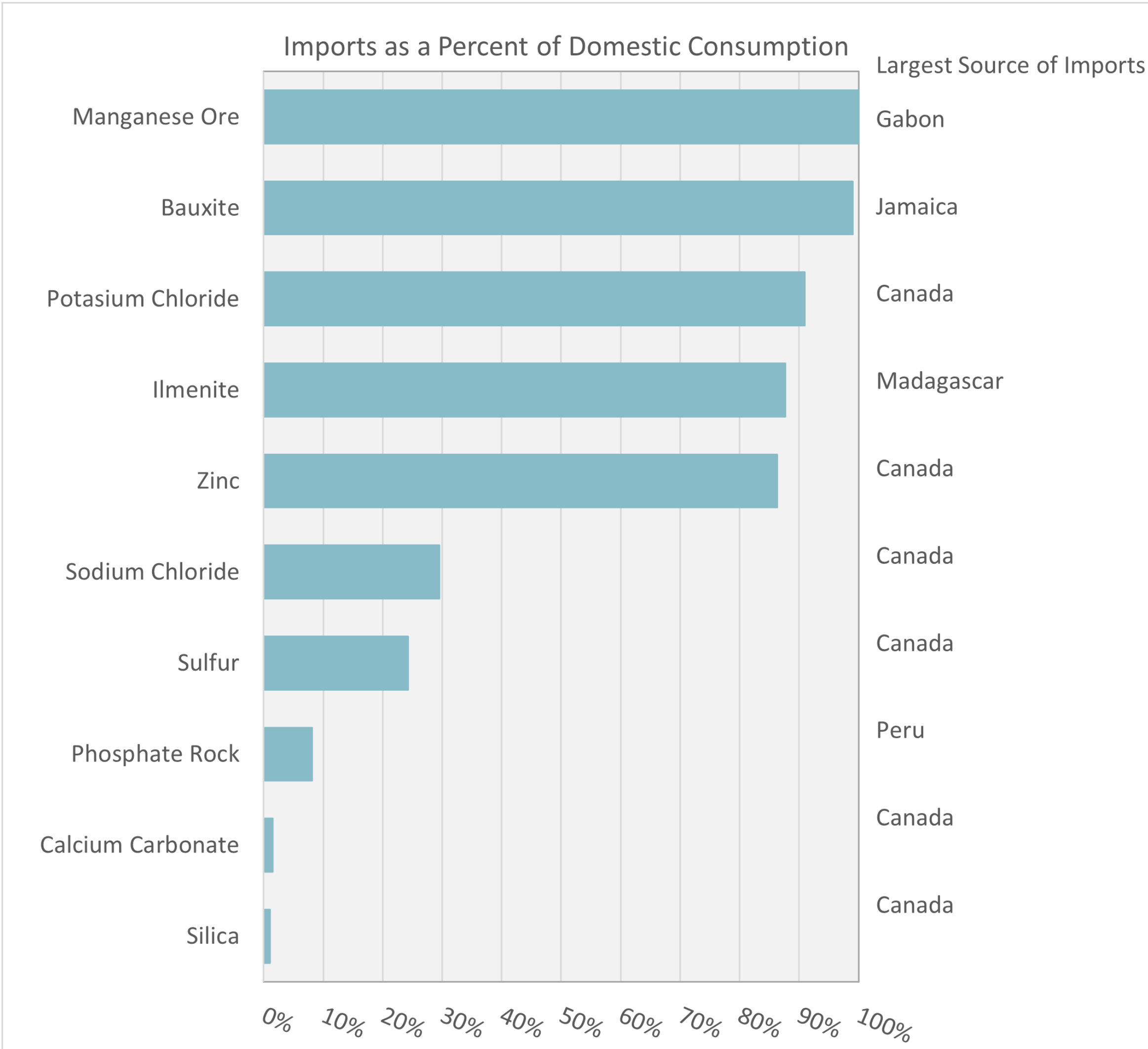


Figure 3-12. U.S. Net Import Reliance for Raw Materials Used in the Production of Water Treatment Chemicals (2019)

Risks to the supply of manufactured chemicals depend not only on the vulnerability of the chemical itself, as characterized by the intrinsic vulnerability rating, but also the vulnerability of the raw materials and precursors needed to manufacture these chemicals. This dependence was incorporated into the relative risk evaluation framework by assigning a vulnerability rating to a manufactured chemical that was the greater value of the intrinsic vulnerability rating or the vulnerability rating of any raw material or precursor needed to manufacture the chemical. Figure 3-13 lists the 15 manufactured chemicals that were assigned a vulnerability rating higher than the chemical's intrinsic vulnerability rating, and equal to the greatest vulnerability rating for a precursor or raw material need to manufacture the chemical.

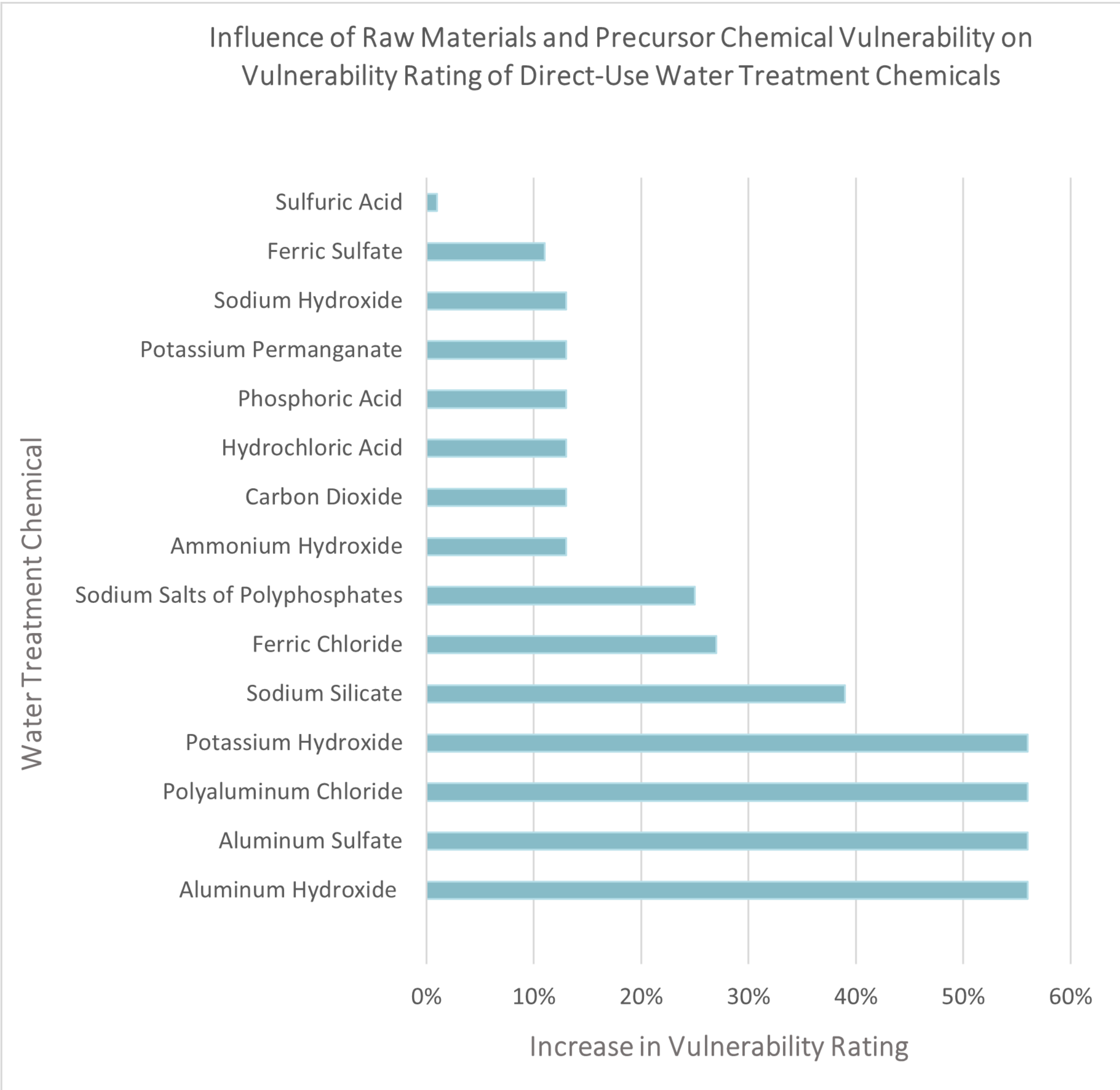


Figure 3-13. Influence of Input Vulnerability on the Vulnerability Rating of Direct-Use Chemicals

4 SUMMARY AND CONCLUSIONS

Reliable availability of drinking water treatment chemicals is necessary for the uninterrupted operation of critical water services that support public health, environmental protection, and the national economy. Historically, true water treatment chemical disruptions in the United States have been intermittent, mostly regional in nature, and relatively uncommon. Recent events, including the COVID-19 pandemic have offered key insights into characteristics of the chemical industry that impact the supply of water treatment chemicals. These insights, along with additional, detailed information from past events, records of production and trade, and a description of the primary manufacturing processes have been captured in this study to understand the unique features of each chemical supply chain. The information documented in this report can serve as a planning tool for assessing future risk of water treatment chemical supply disruptions.

Most of the water treatment chemicals researched as part of this study have complex, multi-step supply chains that rely on inputs from multiple companies and possibly multiple countries. Despite the distinct nature of each supply chain, overarching factors that inform the risk of future supply disruption emerged from this research. These findings are discussed below.

4.1 Nature of the Water Treatment Chemical Supply Chain

Most of the water treatment chemicals and precursors evaluated in this study are widely used in other, competing industries. It is rare that use of a chemical for water treatment accounts for most of the demand in the commercial market. In addition to holding a small market share, a chemical must meet certain standards to be used for water treatment, which generally requires additional certifications and processing. These market characteristics for water treatment chemicals can result in fluctuations in the availability and price of chemicals certified for use in drinking water treatment.

Water Treatment Chemical Supply Chain Profiles

Detailed supply chain profiles of each of the 46 chemicals and raw materials included in this study can be viewed at Water Treatment Chemical Supply Chain Profiles. The information in these profiles can help to contextualize the market and global conditions that may play a role in their availability, guiding efforts to plan for future price increases and shortages.

The supply chain analysis developed as part of this research effort provide insight into the characteristics of chemical supply chains that impact their risk of disruptions. It also identified a few foundational chemicals such as chlorine and phosphate rock that are essential to the production of several other water treatment chemicals, while also being essential to other competing industries, most of which have a larger market share than the water sector.

4.2 Key Risk Factors

This study utilized a relative risk evaluation framework to identify water treatment chemicals with supply chain characteristics that may increase their relative risk of future supply disruptions. Three risk parameters (criticality, likelihood, and vulnerability) were evaluated to determine the relative risk ranking for each chemical.

This study evaluated a broad range of chemicals and conditions that resulted in disruptions in the supply of those chemicals, revealing several factors that can increase relative risk of disruptions:

- Reliance on import of raw materials or precursors needed for manufacture. This factor is particularly important when there is competing demand for those materials. Import dependencies can be exacerbated by trade policies that impede access to major global producers. As an example, China is a major producer of mono- and disodium phosphate but import of these commodities from China are subject to a 25% tariff.

- Availability of domestic product. In some key manufacturing sectors, captive consumption is known to utilize a significant portion of overall domestic production capacity. Examples of chemicals that have significant captive consumption include phosphate rock, phosphoric acid, and chlorine.
- Limited or geographically concentrated domestic manufacturing capacity. Industries that are concentrated in regions of the country that frequently experience extreme weather events may be at greater risk of supply disruptions that could have widespread impacts. For example, a significant percentage of chlor-alkali production occurs in the Gulf Coast region, and extreme weather events in this region have resulted in national disruptions in the supply of chlor-alkali chemicals.
- Dependence on production of a higher value commodity. Fluctuation in demand for a higher value product can impact availability of a water treatment chemical that is a byproduct of the primary industry, even when demand for the water treatment chemical remains unfilled. This was exemplified by the decrease in availability of carbon dioxide that resulted from a decrease in demand for ethanol, the primary market that drives production of purified carbon dioxide, during the COVID-19 pandemic.
- Competition for available supply, especially when competition is from other critical infrastructure sectors. The most notable example from this study was the strain on the supply of LOX during the COVID-19 spike in summer 2021. Available LOX supplies were prioritized for the healthcare sector, which resulted in reduced allocations for water system customers, even though they were prioritized right behind healthcare.
- Reliance on strained or inadequate logistics, in particular, transport of bulk commodities. This factor impacts many, if not all, chemical industries. Congested railways and an insufficient number of commercial truck drivers with Hazmat certifications has created bottlenecks in supply chains, leading to extended lead times and delayed deliveries.

4.3 High Risk Chemicals

As part of this review, chemicals important to the water sector that may be at higher relative risk of future supply disruptions were identified. While none of the chemicals were assessed to have a high overall relative risk based on the characteristics evaluated, the separation of chemicals into low, moderate-low, and moderate-high tiers may help identify supply chain susceptibilities and opportunities for future research. However, it is important to remember that risk does not equal likelihood. While historic supply chain disruptions were used to assess likelihood of potential future supply disruptions, historic behavior is not a definitive predictor of future events. Case in point, several chemicals identified as being at moderate-low relative risk of a supply disruption, such as LOX and carbon dioxide, experienced shortages during the unique conditions caused by the COVID-19 pandemic. While the likelihood was determined to be high for these chemicals, the other two risk parameters, criticality and vulnerability were lower, resulting in a lower relative risk rating.

Three chlor-alkali chemicals, chlorine, sodium hydroxide, and sodium hypochlorite, all critical to water treatment, were assessed as three of the six chemicals at greatest potential risk of a future supply disruption. This result is due to the criticality of these chemicals both as direct use treatment chemicals and precursors to the production of other water treatment chemicals, and the history of repeated supply disruptions of all three chemicals. Of the other three chemicals with a moderate-high relative risk, two are phosphate-based chemicals (phosphoric acid, and disodium phosphate). This result is due to the history of shortages and challenges in obtaining necessary inputs for manufacturing. Specifically, there is high demand for the primary input (phosphate rock) to the manufacture of these two chemicals, which results in some manufacturers relying on imports from highly competitive international markets. In the case of disodium phosphate, there are very few domestic manufacturers, and there is a significant barrier to trade (high tariff) for this chemical from the largest global producer, China (USITC, 2022). The sixth chemical considered moderate-high relative risk is DADMAC, the precursor to polymer polyDADMAC. This result is due to a number of complex factors, including: a limited number of domestic manufacturers, precursor dependence on production of other higher value commodities (petroleum byproducts), production capacity concentrated in an area prone to extreme weather, a history of significant price increases, and widespread use by the water sector.

These results echo the findings of the COVID-19 Water Sector Survey conducted by EPA in 2020 (EPA, 2021), which indicated concern among CWSs regarding future supply disruptions of chlorine, sodium hypochlorite, and polymers. These results also build upon the results of the AWWA October 2021 COVID survey, indicating concern about reliable availability of chlorine and sodium hypochlorite in late 2021 (AWWA, 2021b). Additionally, an earlier study of chemical supply chain risks in the UK came to similar findings, ranking phosphoric acid first with respect to the risk of supply disruptions, followed by polyamines, chlorine, and polyDADMAC (Dillon, et al., 2015).

4.4 Knowledge Gaps

The significant supply chain disruptions experienced between 2020 and 2022, along with concern about availability and pricing of critical water treatment chemicals indicate that a fuller understanding of water treatment chemical supply chains is necessary. While this report is intended to provide critical information needed by the water sector to plan for future supply disruptions, there are important gaps in the information available about water treatment chemical supply chains.

There is no readily available source of comprehensive, annual production data for all critical water treatment chemicals. While the CDR does provide some chemical production data, it is incomplete because companies can withhold production data based on CBI claims while other chemicals are not covered by the CDR rule. Furthermore, the production data available through CDR is typically several years old. There may be insufficient information to estimate the percentage of domestic production of a given chemical that is destined for the commercial market versus captive consumption. This information is essential to understand the quantity of water treatment chemicals that are truly available.

There are also data gaps with respect to consumption and demand. Currently, there are no national estimates of annual consumption of a given chemical by the water sector. Identifying the chemicals used in the greatest quantities by the water sector could help prioritize further efforts to characterize chemical supply chains. Along with this, a clearer picture of the overall market share consumed by the water sector would offer greater clarity on how to prioritize future needs and evaluate risk.

Several potential risks, based on critical infrastructure interdependencies, were not evaluated as part of this study. One example that could pose significant risk of supply chain disruption is the price and delivery of energy. Many chemical manufacturing processes are energy-intensive, with considerable manufacturing costs attributable to the cost of energy. This risk could extend to logistics concerns and the price of fuel for transportation. Another example of a factor beyond the scope of this study is the purposeful disruption of communications networks and business software. This risk is real and potentially significant, as seen in a recent event where chemical manufacturers which serve the water sector were the victims of a ransomware attack (Bomgardner, 2021). Finally, there is a risk that producers or suppliers may cease operations for financial or other reasons, such as changing business priorities or loss of operating permits (Simchi-Levi et al., 2014). While these potential risks are acknowledged, there is an incomplete understanding of the significance of these risks to the availability of water treatment chemicals.

Progress in filling these knowledge gaps will enable water sector and chemical sector partners to better recognize the conditions that could result in a supply disruption with the potential to impact water system operations.

5 PRACTICAL APPLICATIONS

The complexities and interdependencies of modern water treatment chemical supply chains puts them at risk of supply disruptions. While the circumstances that lead to supply disruptions are beyond control, there are steps the water sector, including EPA and individual water systems, can take to prepare for and respond to supply chain disruptions.

5.1 EPA Role in Assessing National Risk of Supply Disruptions

The relative risk evaluation results presented in this report represent a national view of the risk of disruptions in the supply of water treatment chemicals. This understanding enables EPA to take meaningful action to improve the resilience of water treatment chemical supplies. Specific EPA initiatives supported by this assessment include:

- Policy development: EPA can advocate for policies that address some of the risk factors identified in this report. As an example, EPA has used these results to demonstrate that certain regulatory programs could strain availability and increase prices of critical water treatment chemicals, and advocated for a measured approach that avoids these unintended consequences.
- Resource development: EPA has used the information contained in this report and the accompanying water treatment chemical profiles to develop resources to help individual water systems improve their supply chain resilience. As an example, EPA developed the Chemical Suppliers and Manufacturers Locator Tool (EPA, 2022b), which can help individual water systems identify primary and backup chemical suppliers. EPA intends to continue to expand the water treatment chemicals included in the Locator Tool using the information developed under this study.
- Technical assistance: EPA has developed a robust program to support water systems facing supply chain challenges (see callout box at the end of this section). The understanding that EPA developed through the information summarized in this report and the accompanying water treatment chemical profiles was essential to respond quickly and effectively to requests for technical assistance from individual water systems since 2020. EPA intends to continue to expand the knowledge base of chemical supply chains and improve technical assistance capabilities.

5.2 Water System Role in Assessing Local Risk of Supply Disruptions

While the national level risk evaluation presented in this report provides a useful benchmark, the actual risk that a supply disruption will impact a specific water system are highly specific to that system. A system-specific risk assessment of chemical supplies can help focus efforts to build supply chain resilience. Factors to consider in such a risk assessment include:

- Number of suppliers: Inventory the number of suppliers capable of delivering the water treatment chemical to the system. In general, a distribution facility will deliver to customer within a 5 hour drive, which allows drivers to make a delivery and return to the distribution center without exceeding the 11-hour limit for hours driven without a 10-hour break. Also confirm that nearby suppliers can deliver the chemical using a method compatible with the water system's infrastructure (e.g., bulk delivery, containerized chemicals).
- Diversification of suppliers: Determine whether the suppliers in the region are receiving chemicals from a variety of producers. If all regional suppliers rely on a single producer, that can increase vulnerability to supply disruptions.

Chemical Suppliers and Manufacturers Locator Tool

This tool allows water and wastewater utilities to search for suppliers and manufacturers across the U.S. that may be able to fulfill their chemical supply needs and increase resilience to supply chain disruptions. This tool can be useful to water and wastewater utilities in finding alternative chemical suppliers if their primary supplier is unable to deliver.

https://www.epa.gov/waterutilityresponse/chemical-suppliers-and-manufacturers-locator-tool

- Supplier performance: Review the performance history of current or potential chemical suppliers. A history of delayed deliveries, unexpected price increases, declarations of force majeure, poor communication, or other poor performance indicators could lead to or exacerbate supply chain challenges.
- Transportation infrastructure: Evaluate the resilience of transportation resources used to transport chemicals from the supplier to the water system, and from the chemical producer to the supplier. Reliance on a single transportation resource (e.g., a single rail line) can increase vulnerability to supply disruptions.
- Geographic considerations: Evaluate whether the geographic location of a water system could present challenges to the availability or delivery of water treatment chemicals. Water systems in regions that are vulnerable to natural disasters (e.g., hurricanes, wildfires, flooding) could also be at increased risk of supply disruptions. Also, producers that are in such regions might be more vulnerable to disruptions in production, and this could impact availability of water treatment chemicals 100's of miles away.
- Regional experience: Discuss supply challenges with other water systems in the region or the state Water and Wastewater Agency Response Network (WARN). These experiences can provide insight into the types of supply challenges that might be likely to occur in the future.
- Periodic review: Changes in chemicals used, quantity requirements, and contracting and procurement policies may change a system's supply chain risk profile. Likewise, there may be changes in the suppliers, producers, and transportation resources that service the system's region. Reassessing supply chains and the associated risk of disruptions on a routine basis ensures that efforts to bolster supply chain resilience are focused on the greatest risks.

Additional Resources to Build Supply Chain Resilience and Respond to Supply Challenges

- Supply Chain Resilience Guide for Water and Wastewater Utilities provides actionable guidance for improving water system resilience to supply disruptions.
- Case Studies provide real-world examples of individual water systems navigating supply chain challenges and building resilience.
- Water Treatment Chemical Suppliers and Manufacturers Locator Tool is an interactive mapping tool that can be used to identify nearby chemical manufacturers and suppliers.
- Current Supply Chain Disruptions that could impact water systems are tracked and reported in a central location. New information regarding supply disruptions can be reported to: SupplyChainSupport@epa.gov.
- A Platform for Coordinating Supply Chain Efforts has been established to facilitate information sharing between EPA and water systems, and between the water and chemical sectors. Requests to join the effort can be sent to: SupplyChainSupport@epa.gov.
- Section 1441 of the Safe Drinking Water Act provides EPA with authority to issue a certification of need to a water system if a necessary water treatment chemical is not available.
- The Defense Production Act authorizes the President to require the preferential acceptance of contracts and orders necessary to support the national defense, including critical infrastructure.
- Contact SupplyChainSupport@epa.gov for direct technical assistance from EPA in resolving supply challenges.

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7 GLOSSARY

Captive consumption. The internal transfer of manufactured products within a company for significant production of derivative products.

CAS Registry Number. A unique numerical identifier which designates a unique substance, assigned to every chemical substance identified in open scientific literature.

Chlor-alkali process. A process used in the manufacture of chlorine, hydrogen, and sodium hydroxide (or potassium hydroxide) through the electrolysis of a sodium (or potassium) chloride brine.

Community water system. A public water system that provides water for human consumption through pipes or other constructed conveyances and has at least fifteen service connections or regularly serves at least twenty-five individuals, and which serves the same population year-round (as defined in SDWA section 1401(15)).

Derivative chemical. A chemical that is derived from a parent chemical through one or more chemical reactions and retains one or more structural similarities to the parent chemical.

Force majeure. A provision of a contract that provides relief from contract obligations in the instance of an extraordinary event which prevents one or both contract parties from completing their contractual obligations. Interpretations of events characterized by force majeure vary based on jurisdiction.

Input. A raw material, chemical intermediate, or any other resource utilized in the production of a finished chemical.

Manufacturer/Producer. An entity that produces chemicals from raw or prepared materials through a technical process involving process equipment, energy, labor, or other resources.

Precursor. A chemical that is utilized in the chemical reaction to produce another chemical compound.

Raw material. An unprocessed material found in the environment that can be used directly or extracted and used in production of other materials.

Supplier. An entity that sells chemicals on the commercial market. The supplier may be a manufacturer or producer, or the supplier may purchase chemicals from a manufacturer and repackage or simply bring the chemicals to market.

Supply chain. The network of all resources (materials, companies, technology, transportation) involved in the creation and delivery of a product.

Toxic Substances Control Act (TSCA). Section 8 (b) of the Toxic Substances Control Act (TSCA) requires EPA to compile, keep current and publish a list of each chemical substance that is manufactured or processed, including imports, in the United States for uses under TSCA. The Chemical Data Reporting (CDR) rule is required by section 8 (a) of the TSCA.

Water treatment chemical. Any material (raw element or manufactured chemical) used as part of water treatment process.

Water and Wastewater Systems Sector (water sector). One of the critical infrastructure sectors formally designated by the Department of Homeland Security, Cybersecurity and Infrastructure Security Agency, that includes the Nation’s drinking water and wastewater infrastructure.

8 APPENDIX A

The following discussion presents the detailed rating approach for the three main risk parameters (criticality, likelihood, vulnerability).

The parameter multipliers assigned are only meant to determine the relative influence of the input attribute on the output and should not be interpreted as estimates of absolute risk, due to various assumptions made. For each chemical, incorporation of new information and additional data points may lead to adjustments to the multiplier used for a given parameter attribute.

Criticality

Criticality is a measure of the importance of a specific chemical to the water sector, either as a direct use chemical for treatment of drinking water or wastewater or as a precursor to the production of direct use treatment chemicals. The raw rating for criticality is “10” and the following multipliers were applied according to the listed attributes. Descriptive characterization of the multipliers used for the criticality risk parameter are presented below in **Table A-1**. In cases where more than one multiplier could apply, the largest multiplier was used. Each attribute multiplier range was adjusted to provide adequate separation of qualitative characteristics while avoiding an underestimation of attribute and parameter risk.

Table A-1. Attributes Used to Rate Criticality

Criticality Attributes		
Unit Process Weight		**Multiplier**
1.	Chemical is used for disinfection, coagulation, pH adjustment, post-treatment stabilization, or corrosion control	1.0
2.	Chemical is used in a process that could potentially be temporarily suspended (e.g., pre-treatment, fluoridation)	0.7
3.	Chemical is used only periodically (i.e., membrane cleaning, resin regeneration)	0.5
Extent of Use Weight		**Multiplier**
1.	Chemical is widely used in water treatment	1.0
2.	Chemical is moderately used in water treatment	0.9
3.	Chemical is infrequently used in water treatment	0.8
Number of Applications Weight		**Multiplier**
1.	Chemical is used in four or more applications	1.0
2.	Chemical is used in fewer than four but more than one application	0.95
3.	Chemical is used in only one application	0.9

Likelihood

Historic supply chain disruptions were categorized into one of the five following groups: a rating of 10 for widespread shortage(s) in the U.S.; a rating of 9 for regional shortage(s) in the U.S.; a rating of 7 for instances where force majeure notices were issued or concerns of potential disruption were raised; a rating of 6 for significant price increase; and a rating of 5 for no supply disruptions or significant price increase in the domestic market. The raw rating for likelihood is "10" and the following multipliers were applied according to the listed criteria. The multipliers used for the likelihood risk parameter are described in **Table A-2**. Since historic supply chain disruptions were not present for the supply chain of every chemical included in the study, the data multiplier range was adjusted to avoid an overestimation of risk in supply chains that had experienced widespread disruption in the past and an underestimation of likelihood as a factor of overall relative risk in instances where supply chains were found to have no recent history of disruption.

Table A-2. Attributes Used to Rate Likelihood

Likelihood Attributes		Multiplier
1.	Chemical market has experienced at least one widespread disruption to domestic supply (2000-2022)	1.0
2.	Chemical market has experienced at least one regional supply disruption (2000-2022)	0.9
3.	Chemical market producers or suppliers have invoked force majeure or raised concerns about potential disruptions, including trade disputes (2000-2022)	0.7
4.	Chemical market has experienced significant price spikes (2000-2022)	0.6
5.	Chemical market has no know history of supply disruptions or significant price increase (2000-2022)	0.5

Vulnerability

In this supply chain risk evaluation, vulnerability considers the characteristics of the entire market for a specific chemical that make it more or less resilient to supply disruptions. The raw rating for vulnerability is "10" and the following multipliers were applied according to the listed attributes, as described in **Table A-3**. In cases where more than one multiplier could apply, the largest multiplier was used. Each attribute multiplier range was adjusted to provide adequate separation of qualitative characteristics while avoiding an underestimation of attribute and parameter risk.

Table A-3. Attributes Used to Rate Vulnerability

Vulnerability Attributes		
Import Dependence & Trade Policies Weight		**Multiplier**
1.	High import dependence and unfavorable trade policies: imports for domestic consumption account for greater than 20% of U.S. consumption, and U.S. import tariff on the largest global exporter (a country that controls more than 25% of the global market) is equal to or greater than 5%	1.0
2.	High import dependence and favorable trade policies: imports for domestic consumption account for greater than 20% of U.S. consumption, and U.S. import tariff on the largest global exporter is less than 5%	0.9
3.	Low import dependence: imports for domestic consumption account for less than 20% of U.S. consumption	0.8
U.S. Production Diversity Weight		**Multiplier**
1.	The number of U.S. production locations is fewer than 10 and the production locations are geographically concentrated	1.0
2.	The number of U.S. production locations is fewer than 10 and the production locations are geographically distributed or the number of U.S. production locations is equal to or greater than 10 and the production locations are geographically concentrated	0.9

Vulnerability Attributes		
U.S. Production Diversity Weight		**Multiplier**
3.	The number of U.S. production locations is equal to or greater than 10 and the production locations are geographically distributed	0.8
Domestic Competition Weight		**Multiplier**
1.	The water sector represents less than 10% of U.S. consumption and there is significant competition for the chemical from another critical infrastructure sector (i.e., healthcare, food and agriculture, energy, defense, transportation, or critical manufacturing)	1.0
2.	The water sector represents greater than 10% of U.S. domestic consumption and there is significant competition for the chemical from another critical infrastructure sector; or the water sector represents less than 10% of U.S. domestic consumption, but there is no significant competition for the chemical from another critical infrastructure sector.	0.9
3.	The water sector represents greater than 10% of U.S. domestic consumption and there is no significant competition for the chemical from another critical infrastructure sector	0.8
Stability in Storage Weight		**Multiplier**
1.	Chemical has a shelf-life less than one month	1.0
2.	Chemical has a shelf-life less than six months but greater than one month	0.9
3.	Chemical has a shelf-life greater than six months	0.8