TECHNICAL REPORT NO. 62

IMPACTS OF CHLORIDE ON THE NATURAL AND BUILT ENVIRONMENT

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INTRODUCTION 1

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1.1 PURPOSE OF THIS REPORT

This Technical Report presents the results of a review of the relevant technical literature regarding the impacts of chloride and chloride salts on the natural and built environment. It discusses information needed to assess the potential consequences of increasing concentrations of chloride in surface waters and groundwater on the physical, chemical, and biological integrity of ecosystems and the structural integrity of infrastructure in the Region.

Concentrations of chloride in surface and groundwater in southeastern Wisconsin have been increasing over time. The Southeastern Wisconsin Regional Planning Commission (Commission) has documented these trends for portions of the Southeastern Wisconsin Region (Region) in several reports.[1] Chloride conditions and trends have been documented for the entire Region as part of the Chloride Impact Study developed by the Commission.[2] Trends of increasing chloride concentrations in and around the Region have also been reported in other research.[3]

Chloride contributions to surface waters and groundwater can come from a variety of sources, including road salt applied for anti-icing and deicing of public and private roads, sidewalk, and parking lots; water softening systems and other sources that discharge to sanitary sewers or private onsite wastewater

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[1] *See for example, SEWRPC Technical Report No. 39,* Water Quality Conditions and Sources of Pollution in the Greater Milwaukee Watersheds, *November 2007; SEWRPC Community Assistance Planning Report No. 315,* A Water Resources Management Plan for the Village of Chenequa, Waukesha County, Wisconsin, *June 2014*; *SEWRPC Community Assistance Planning Report No. 316*, A Restoration Plan for the Root River Watershed, *July 2014; and SEWRPC Community Assistance Planning Report No. 330,* A Restoration Plan for the Oak Creek Watershed, *December 2021.*

[2] *SEWRPC Technical Report No. 63,* Chloride Conditions and Trends in Southeastern Wisconsin, *in preparation.*

[3] *See for example, Richard C. Lathrop, "Chloride and Sodium Trends in the Yahara Lakes,* Research Management Findings, *No.12, Wisconsin Department of Natural Resources, June 1998; S.R. Corsi, L.A. De Cicco, M.A. Lutz, and R.M. Hirsch, "River Chloride Trends in Snow-Affected Urban Watersheds: Increasing Concentrations Outpace Urban Growth Rate and Are Common Among All Seasons,"* Science of the Total Environment,*508:488-497, 2015; and J.A. Thornton, T.M. Slawski, and H. Lin, "Salinization: The Ultimate Threat to Temperate Lakes, with Particular Reference to Southeastern Wisconsin (USA),"* Chinese Journal of Oceanology and Limnology, *33:1-15, 2015.*

treatment systems; large agricultural feedlots; fertilizers; landfills; chemical manufacturing; food processing; and deposition from the atmosphere. Increased concentrations of chloride can have several effects on the natural and built environment. It can cause physical and chemical impacts to soil; sediment; surface water resources including streams, rivers, lakes, and wetlands; and groundwater. It can cause biological effects such as acute and chronic toxicity to organisms, reductions in the viability of individual species, and changes to the structure and functioning of aquatic communities and ecosystems. Higher chloride concentrations can damage materials such as metal and concrete, affecting the condition, structural integrity, and useful life of infrastructure such as roadway pavements, water mains, and street and highway bridges. It can also damage private property such as automobiles. Finally, increased chloride levels can affect human activities through impacts on agriculture, drinking water, human health, and the aesthetics of the environment.

1.2 RELATIONSHIP OF THIS REPORT TO THE CHLORIDE IMPACT STUDY

This Technical Report presents some of the findings from the Chloride Impact Study.[4] This Study was initiated due to heightened public concern over the growing use of road salt and evidence of increasing chloride concentrations in surface water and groundwater within the Southeastern Wisconsin Region. The findings of this Study are being presented in a series of reports.

Major objectives of the Chloride Impact Study include:

1. Documenting historical and existing conditions and trends in chloride concentrations in surface and groundwater in the Southeastern Wisconsin Region

2. Evaluating the potential for increased amounts of chloride in the environment to cause impacts to surface water, groundwater, and the natural and built environment in the Region

3. Identifying the major sources of chloride to the environment in the Region

4. Investigating and defining the relationship between the introduction of chloride into the environment and the chloride content of surface and groundwater

5. Developing estimates of chloride loads introduced into the environment under existing conditions and forecasts of such loads under planned land use conditions

6. Evaluating the potential effects of climate change on the major sources of chloride under planned land use conditions

7. Reviewing the state-of-the-art of technologies and best management practices affecting chloride inputs to the environment and developing performance and cost information for such practices and technologies

8. Exploring legal and policy options for addressing chloride contributions to the environment

9. Developing and evaluating alternative chloride management scenarios for minimizing impacts to the environment from chloride use while meeting public safety objectives

10. Presenting recommendations for the management of chloride and mitigation of impacts of chloride on the natural and built environment

This Report reviews literature on the impacts of chlorides on the natural and built environment. By identifying and describing the reported impacts of contributions of chloride to the environment, it provides a basis for addressing Objective 2. It also contributes to addressing Objectives 8 and 10 by providing information that will be useful for identifying and evaluating potential consequences of alternative management strategies for chloride.

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[4] *SEWRPC Planning Report No. 57,* A Chloride Impact Study for Southeastern Wisconsin, *in preparation*.

1.3 REPORT FORMAT AND ORGANIZATION

This Report summarizes the impacts of chlorides on the natural and built environment. It is based on a review of the relevant scientific and technical literature and is organized into five chapters.

Following this introductory chapter, Chapter 2 reviews the physical and chemical impacts of chloride on the natural environment. This review describes the impacts of chlorides on lakes, streams and rivers, wetlands, groundwater, and soils.

Chapter 3 reviews the impacts of chloride on biological systems. This review discusses the toxicity to and other effects of chloride compounds on organisms. It also includes discussions of impacts at higher levels of biological organization such as communities and ecosystems.

Chapter 4 reviews the impacts of chlorides on infrastructure and the built environment. This review describes the effects of chloride on concrete and metal. It also describes the impacts to public infrastructure and private property that can result from exposure to chlorides.

Chapter 5 reviews the impacts of chlorides on humans and human activities. This reviews the impacts that excessive chloride in the environment can have on agriculture, drinking water, human health, and the aesthetics of the environment.

PHYSICAL AND CHEMICAL IMPACTS OF CHLORIDE ON THE NATURAL ENVIRONMENT

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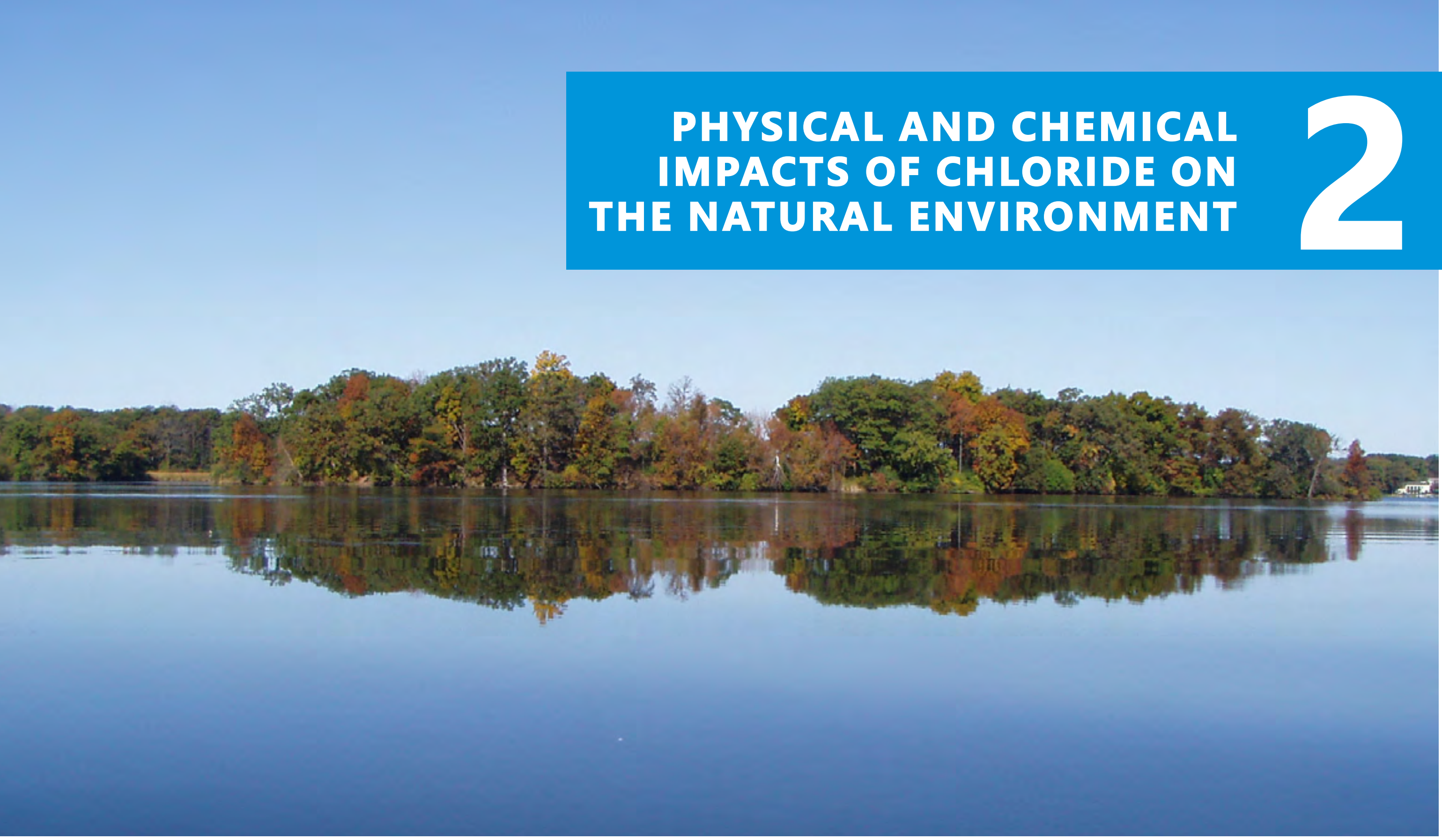

Credit: SEWRPC Staff

2.1 INTRODUCTION

Chlorine is the 20th most abundant element on the earth. Because it is a highly reactive element, it is never found in nature as elemental chlorine gas. Instead, it is often found as chloride ions. These ions have a negative charge and can form ionic compounds with positively charged ions. Chloride readily forms salts with metals, especially alkaline metals such as sodium and potassium and alkaline earth metals such as magnesium and calcium. Commonly occurring chloride salts are highly soluble in water and are present in some concentration in all surface waters. Only a few chloride salts, such as silver chloride (AgCl),[5] lead (II) chloride ($PbCl_2$), and mercurous chloride (Hg_2Cl_2) are poorly soluble in water.

Chloride and chloride salts can affect the physical and chemical properties of water. Additions of chloride salts contribute to the salinity of water. The freezing point of water is lowered by about 0.36 degrees Fahrenheit (°F) for each milligram per liter (mg/l) increase in salinity.[6] Salinity also increases the density of water. This is discussed in greater detail later in this chapter in the section on chloride impacts on lakes. The cations associated with chloride can engage in chemical reactions in water, soil, and sediment. This can cause increases in the acidity of water.[7]

Chloride is not decomposed, chemically altered, or removed from water as a result of natural processes. Chloride concentrations in inland freshwater bodies due to natural sources are typically less than 20 mg/l.[8] Natural chloride concentrations in these surface waters reflect the composition of the underlying bedrock and soils as well as deposition from precipitation events. Waterbodies in southeastern Wisconsin typically

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[5] *Acronyms and abbreviations used in this report are defined in Appendix A.*

[6] *R.G. Wetzel,* Limnology (3rd Edition), *Elsevier, 2001.*

[7] *See, for example, S. Löfgren, "The Chemical Effects of Deicing Salt on Soil and Stream Water of Five Catchments in Southeast Sweden,"* Water, Air, and Soil Pollution*, 130:863-868, 2001; D.K. Jones, B.M. Mattes, W.D. Hintz, A.B. Stoler, L.A. Lind, R.O Cooper, and R.A. Relyea, "Investigation of Road Salts and Biotic Stressors on Freshwater Wetland Communities,"* Environmental Pollution*, 221:159-167, 2017.*

[8] *See references in Table 1 of W.D. Hintz and R.A. Relyea, "A Review of the Species, Community, and Ecosystem Impacts of Road Salt Salinization in Freshwater,"* Freshwater Biology*, 64:1,081-1,097, 2019.*

have very low natural chloride concentrations due to the dolomite bedrock found in the Region. These rocks are rich in carbonates and contain little chloride.

Chloride can be released into the environment from several sources. Natural sources include dissolution of chloride-bearing rock, such as halite, and salts contributed to the atmosphere from ocean sprays (see Figure 2.1). These are minor sources of chloride to the environment in southeastern Wisconsin because chloride is a minor component of the Region's underlying bedrock, and the Region is located far from the nearest ocean. There are several anthropogenic sources including application of chloride salts for deicing roads, parking lots, driveways and other impervious surfaces; use of salt to recharge water softeners; use of salts in food processing and other industrial processes; and applications of potash (potassium chloride) to soils as fertilizer (see Figure 2.2).

This chapter describes pathways through which chloride may move into and through the natural environment and the physical and chemical impacts of chloride on the natural environment. Discussion in the chapter addresses impacts of both chloride and chloride salts. This is important because some impacts resulting from the introduction of chloride are caused by the cation or cations associated with chloride and not by the chloride itself.

2.2 CHLORIDE MOVEMENT INTO AND THROUGH THE NATURAL ENVIRONMENT

The Hydrologic Cycle

Figure 2.3 shows the natural water cycle or hydrologic cycle. Water on Earth is always moving above, on, and below the ground surface. These movements happen over time scales ranging from seconds to thousands of years. As part of this continuous cycle, water also changes state between gaseous, liquid, and solid forms.

Cool temperatures in the atmosphere cause water vapor to condense into droplets, forming clouds. Winds move these clouds around the globe. As the clouds move, the water droplets collide with one another and grow into larger droplets. Eventually, the droplets grow large enough that they fall out of the atmosphere as precipitation—rain, snow, sleet, or hail.

Some precipitation falls on the land surface. From here it can travel in several directions. Some runs off the land and enters streams, rivers, lakes, and wetlands. Much of the runoff entering streams and rivers will flow to the oceans. Other precipitation falling on land will infiltrate into soil. Some of this will be taken up by plants, some will evaporate into the atmosphere, and some will percolate through the soil to join groundwater.

Some precipitation falls directly on waterbodies, including streams, rivers, lakes, wetlands, and the oceans, adding to their volume. Some of the water entering a waterbody may percolate through the waterbody's bed and through the soil to join groundwater.

Water percolating through soil rejoins groundwater. This is eventually discharged to the land's surface through springs and to waterbodies as baseflow to streams, rivers, lakes, and wetlands. Some may also be discharged to the oceans.

Heat will cause water to evaporate from waterbodies and soil. Water will also move from the soil through plants and into the atmosphere through transpiration. This water enters the air as water vapor. Air currents will move this vapor higher into the atmosphere. Cooler temperatures at higher altitudes will cause this vapor to condense forming small droplets.

Pathways of Chloride Through the Environment

The movement of chloride through the environment is intimately tied to the hydrologic cycle. Because of the high solubility of chloride in water, anthropogenic chloride that enters the environment is likely to be transported in liquid water. Thus, some of the paths that chloride travels through the environment will include those portions of the hydrologic cycle that involve water in the liquid state.

Figure 2.1
Natural Sources of Chloride to the Environment

Ocean spray puts chloride into the atmosphere.

Halite is a chloride-containing mineral found in some rocks.

Source: Wikimedia Commons

Figure 2.2
Examples of Anthropogenic Sources of Chloride to the Environment

Winter Deicing Activities

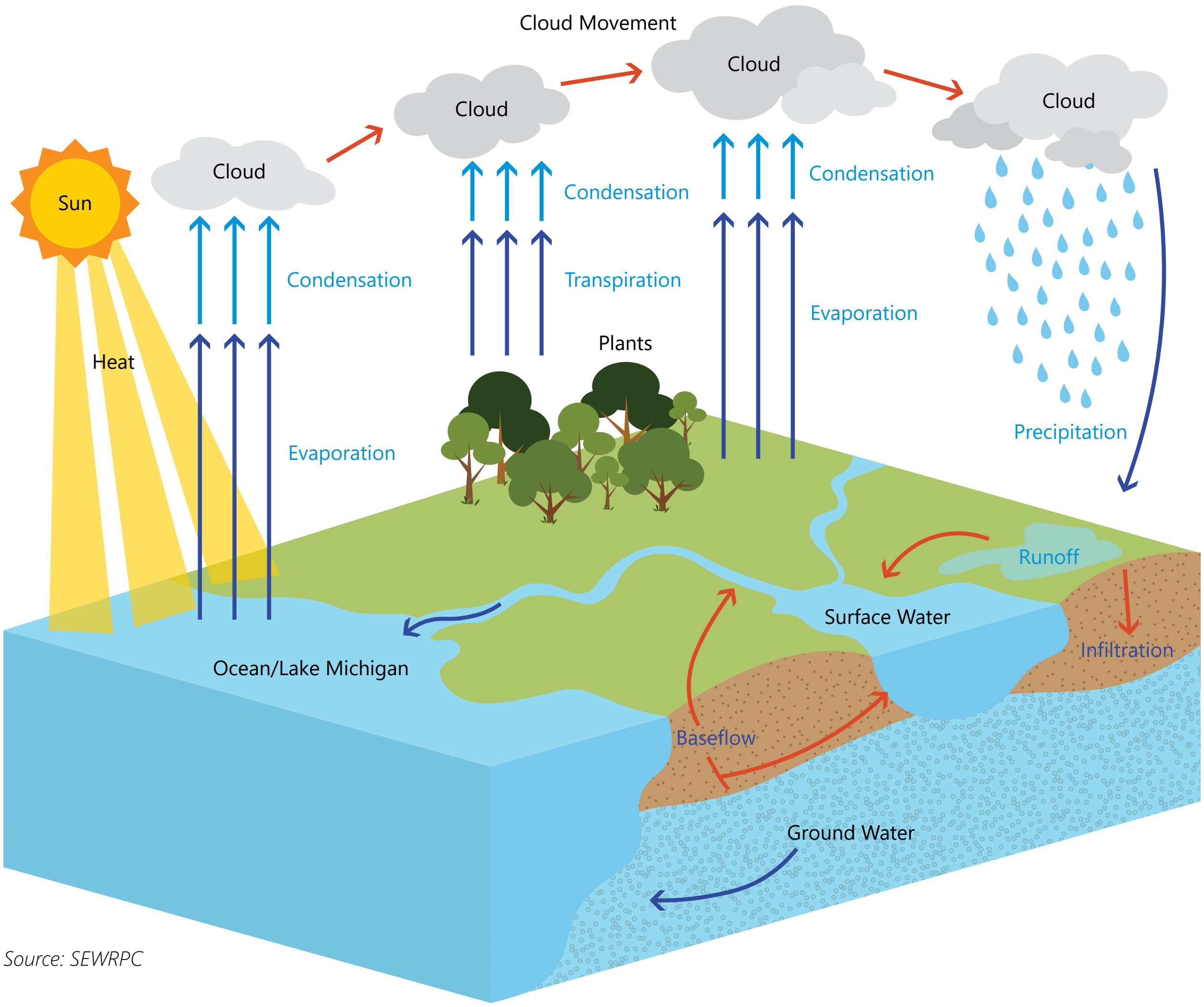
Water Softening

Food Processing

Fertilizer Application

Source: Wikimedia Commons, Wisconsin Salt Wise, and Texas Sea Grant, and the Natural Resource Conservation Service

Figure 2.3
The Natural Hydrologic Cycle



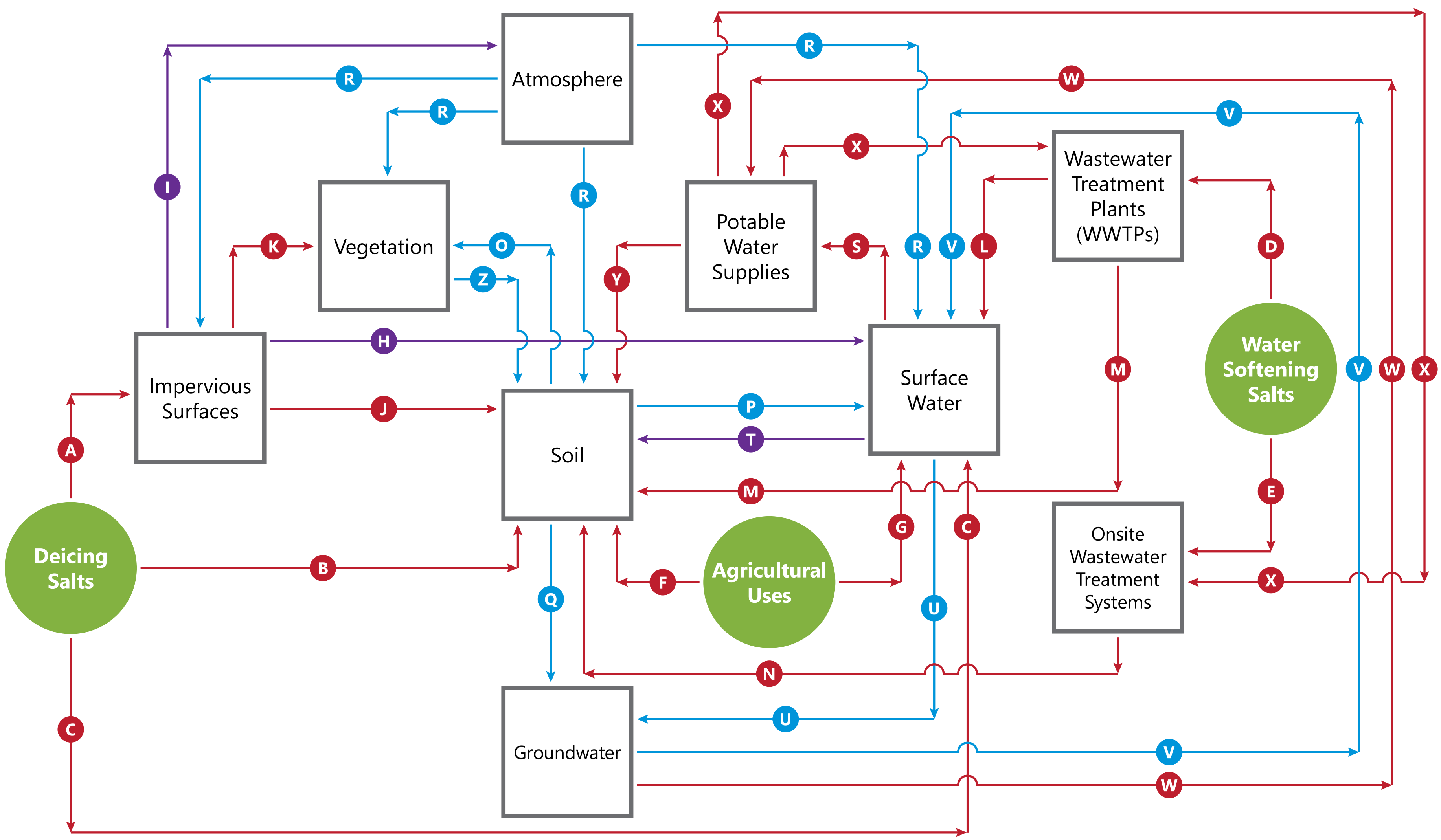
Source: SEWRPC

Figure 2.4 and Table 2.1 illustrate several common pathways through which chloride can move through the environment. Green circles in the figure indicate sources of chloride to the environment. Gray boxes indicate compartments where chloride can be stored. Arrows indicate pathways. Some examples of these pathways are discussed below.

Deicing salt spread on snow or ice will move through the environment via one of several pathways.[9] It can dissolve in melting snow and ice and runoff directly into surface waters. Traffic can splash it into adjacent roadsides where it can be deposited on vegetation or soil. Salt that lands on soil can percolate down into groundwater. Salt laden snow can be removed from roads or parking lots and be transported to another location. At this new location it can melt and enter runoff or percolate into soil. Salt residues on the roadside can be mobilized into the air where wind currents can transport it to other locations where it can dissolve in water from precipitation and either enter runoff or percolate into the soil. While cations from deicing salt such as sodium, calcium, or magnesium may be retained in soil (see the section on impacts to soil and sediment below), chloride ions will tend to move with the water. Thus, chloride in the soils may continue to infiltrate through the soils into the groundwater. Some of the chloride in groundwater may be transported to surface waterbodies in baseflow.

[9] *D.M. Ramakrishna and T. Viraraghavan, "Environmental Impact of Chemical Deicers—A Review,"* Water, Air, and Soil Pollution, *166:49-63, 2005.*

Figure 2.4
Pathways of Chloride Through the Environment



Note: Note: Green circles indicates sources of chloride to the environment. Gray boxes indicate compartments in the environment. Blue arrows indicate paths that are natural processes. Red arrows indicated paths that are human activities. Purple arrows indicate paths that are a combination of natural processes and human activities. The paths are described in Table 2.1.

Source: SEWRPC

Table 2.1
Pathways of Chloride Through the Environment

Path (on Figure 2.4)	Description
A	***Deicing salts*** applied to ***impervious surfaces*** including roads, parking lots, driveways, and sidewalks
B	***Deicing salts*** deposited on ***soil*** during transport or storage
C	***Deicing salts*** carried in runoff from storage facilities to ***surface water***
D	***Water softening salts*** from residential, commercial, institutional sites conveyed in sanitary wastes to ***wastewater treatment plant*** though sanitary or combined sewer system
E	***Water softening salts*** from residential, commercial, institutional sites conveyed in sanitary wastes to ***onsite wastewater treatment system***
F	***Agricultural use:*** chloride in fertilizer or animal wastes applied to ***soil***
G	***Agricultural use:*** chloride in animal wastes carried in runoff from feedlots to ***surface water***
H	Runoff from ***impervious surfaces*** including roads, parking lots, driveways, and sidewalks carried to ***surface water,*** either directly or through ditch or storm sewer systems
I	Traffic or wind mobilizes salts in dust, sprays, and aerosols from ***impervious surface*** to the ***atmosphere***
J	Salt from ***impervious surface*** splashes, sprays, runs off, or is plowed onto ***soil***
K	Salt from ***impervious surface*** splashes or sprays onto ***vegetation***
L	***Wastewater treatment plant*** discharges effluent into ***surface water***
M	1) ***Wastewater treatment plant*** discharges effluent into infiltration pond where it percolates into ***soil*** 2) Exfiltration of ***wastewater*** from sewers into ***soil***
N	***Onsite wastewater treatment system*** discharges effluent into infiltration field in ***soil***
O	Direct uptake of chloride from ***soil*** by ***vegetation***
P	Runoff of water carries chloride from ***soil*** into ***surface water,*** either directly or through ditch or storm sewer system
Q	Infiltration of water containing chloride from ***soil*** into ***groundwater***
R	Dry or wet deposition of chloride from the ***atmosphere*** onto ***impervious surface, surface water, soil,*** and ***vegetation***
S	Pumping of ***surface water*** for use as potable water supply
T	Pumping of water from ***surface water*** for use in irrigation and floods carrying chloride to ***soil***
U	Infiltration of water from ***surface water*** into ***groundwater***
V	Discharge of water as baseflow from ***groundwater*** into ***surface water***
W	Pumping of ***groundwater*** for use as ***potable water supply***
X	Used ***potable water supply*** conveyed to **wastewater treatment plant** or ***onsite wastewater treatment system for treatment***
Y	Application of water from ***potable water supply*** to soils for irrigation or lawn watering
Z	Decomposition of ***vegetation*** returns chloride to ***soil***

Note: Terms in ***bold italics*** indicate environmental compartments shown in Figure 2.4.

Source: SEWRPC

Similar pathways through the environment can be described for chlorides from salts used to recharge water softeners. In an urban setting, the effluent from a water softener is conveyed through a sanitary sewer system to a wastewater treatment plant (WWTP). Treatment at this facility does not remove the chloride from the water and, depending on the treatment process, may increase its concentration due to evaporation of water. Effluent from the WWTP is typically discharged into a surface waterbody or more rarely to infiltration ponds. From either of these receiving points, water may infiltrate into the soil, ultimately carrying chloride into groundwater. In suburban and rural settings, effluent from the water softener is treated in an onsite wastewater treatment system such as a septic tank. Following treatment, it is discharged into the soil via an infiltration system.

While Figure 2.4 shows numerous pathways that chloride can follow through the environment, it is important to note that most of it ultimately ends up in either surface water or groundwater. Numerous factors can affect the movement of chloride through the environment. Different combinations of factors may affect each of the pathways shown in Figure 2.4. Three examples illustrate this point.

The first example of factors impacting chloride movement is how chloride can percolate through soils into groundwater. Factors that affect this movement include:[10]

- The types of soil, sediment, and rock present
- The texture and drainage characteristics of the soil
- The level of soil saturation
- The ion exchange capacity of the soil
- The permeability of the aquifer material
- The direction and velocity of groundwater flow
- The evaporative conditions in soil pores
- The amount of rainfall

The second example of factors impacting chloride movement is how salt can be applied to roads for deicing. Chloride and other materials from the salt can enter into solution after application and be carried as runoff into drainage ditches and surface waterbodies. Several factors influence the concentrations of chloride and salt in runoff and receiving waterbodies, including:[11]

- The length and width of the road treated
- The amount of salt applied
- The drainage pattern and topography of the road and adjacent area
- The discharge rate of the receiving stream
- The rate of temperature increase
- The duration of periods when temperatures are above freezing
- The amount and duration of precipitation

The third example of factors impacting chloride movement is how salt and chloride applied to roads can be mobilized to the atmosphere in sprays and aerosols generated by moving vehicles. This mobilization of salt into the air from roads has been measured as a plume up to 49 feet high.[12] Following this the salts can be transported a considerable distance through the air and deposited nearby on vehicles, soils, vegetation, buildings, infrastructure, or the surface of waterbodies. Several factors affect the distance from the road that spray containing salt will migrate, including:[13]

- The velocity of the vehicles

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[10] *M. Fischel,* Evaluation of Selected Deicers Based on a Review of the Literature, *Colorado Department of Transportation Report No. CDOT-DTD-R-2007-15, 2001.*

[11] *W.S. Scott, "An Analysis of Factors Influencing De-icing Salt Levels in Streams,"* Journal of Environmental Management, *13:269-287, 1981.*

[12] *P.D. Kelsey and R.G. Hootman, "Deicing-Salt Dispersion and Effects on Vegetation Along State Highways Case Study: Deicing-Salt Deposition on the Morton Arboretum," pages 253-277, In F.M. D'Itri (editor),* Chemical Deicers and the Environment, *Lewis Publishers, Ann Arbor, Michigan, 1992.*

[13] *E. McBean and S. Al-Nassri, "Migration Pattern of De-icing Salts from Roads,"* Journal of Environmental Management, *25:231-238, 1987.*

- The wind direction and speed
- The road gradient
- Geometric features of the road

It should also be noted that earthen berms placed along the roadside to protect vegetation from road salt runoff can result in higher aerial-salt plumes because these berms can guide air currents and airborne particles upward.[14] Walls and solid fences placed along highways to reduce noise, restrict access, or promote aesthetics might have a similar effect.

2.3 IMPACTS OF CHLORIDE ON SOIL AND SEDIMENT

Sources of Chlorides to Soil

Chloride can reach soil through several routes. These pathways are illustrated and described in Figure 2.4 and Table 2.1.

Chlorides can be released to soil through spilling of deicing and other salts during storage, loading, or transport. This is shown as path "B" in Figure 2.4. For example, one study found chloride concentrations of 1,200 milligram per kilogram (mg/kg) in the top two inches of soil near salt storage sheds near Kenova, Ontario.[15]

Chlorides can be applied to soil in fertilizers. This is shown as path "F" in Figure 2.4. These applications include chloride applied as a constituent of either chemical fertilizers or manure. Potash is the major chloride containing chemical fertilizer that is used. It is usually applied as muriate of potash, which consists of potassium chloride (KCl). Muriate of potash represents about 95 percent of the potash used in the United States.[16] Chloride constitutes about 47 percent of the weight of potassium chloride. Based on county-level data compiled by the National Agricultural Statistics Service and provided to the Wisconsin Department of Agriculture, Trade and Consumer Protection,[17] about 20.3 million pounds of chloride are applied to agricultural fields as potash fertilizer in the seven county Southeastern Wisconsin Region annually. Manure also contains chloride. For example, it has been estimated that most dairy and feed lot manures contain about 5-10 percent salt.[18] Since chloride constitutes about 60 percent of the weight of salt, this suggests that at least 3 to 6 percent of the weight of these manures consists of chloride. Concentrations of chloride in various manures have been documented at 400 mg/l for horse manure,[19] a mean of 1,028 mg/l for hog

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[14] *Kelsey and Hootman 1992,* op. cit.

[15] *D.J. Racette and H.D. Griffin,* Vegetation Assessment Surveys near the Ministry of Transportation's Longbow Lake Patrol Yard 1988-1989, *Ontario Ministry of the Environment, 1989 cited in N.P. Cain, B. Hale, E. Berkalaar, and D. Morin,* Review of Effects of Road Salts on Terrestrial Vegetation in Canada, *Environment Canada, July 2000.*

[16] *D.L. Armstrong, and K.P. Griffin, "Production and Use of Potassium,"* Better Crops with Plant Food, *82(3):6-8, 1998; S.M. Jasinski, D.A. Kramer, J.A. Ober, and J.P. Searls,* Fertilizers—Sustaining Global Food Supplies, *U.S. Geological Survey Fact Sheet No. 99-155, 1999; J.P. Searls,* Potash, *U.S. Geological Survey Commodity Statistics and Information, 2000; California Fertilizer Foundation,* Plant Nutrients, *2011.*

[17] *Wisconsin Department of Agriculture, Trade and Consumer Protection, "Agricultural Chemical Use,"* Wisconsin Farm Reporter, *20(9):3-4, May 22, 2019; Wisconsin Department of Agriculture, Trade and Consumer Protection, "Agricultural Chemical Use: Barley,"* Wisconsin Farm Reporter, *20(9):4, May 12, 2020; Wisconsin Department of Agriculture, Trade and Consumer Protection, "Agricultural Chemical Use: Soybeans,"* Wisconsin Farm Reporter, *21(10):3-4, June 1, 2021; U.S. Department of Agriculture National Agricultural Statistics Service,* 2017 Census of Agriculture: Wisconsin State and County Data, *April 2019.*

[18] *University of Arizona, "Manure Use and Management Fact Sheet – Animal Management (UA)," cals.arizona.edu/animalwaste/farmasyst/awface8.html, no date, accessed June 3, 2022.*

[19] *S.V. Panno, K.C. Hackley, H.H. Hwang, S.E. Greenberg, I.G. Krapac, S. Landberger, and D.J. O'Kelly,* Database for the Characterization and Identification of NaCl Sources in Natural Waters of Illinois, *Illinois State Geological Survey Open File Series 2005-1, 2005.*

manure,[20] 1,650 mg/l for dairy manure,[21] and 6,000 mg/l in poultry manure.[22] In 2017, manure was applied to over 71,500 acres or about 11 percent of agricultural lands in the southeastern Wisconsin.[23]

Chlorides can be added to soils when deicing salts applied to impervious surfaces such as roads, parking lots, driveways, and sidewalks splashes, runs off, or is plowed with snow to the adjacent roadside. Similarly, chlorides can also be released to soils when snow is removed from impervious surfaces and deposited on snow piles at another location. This is shown as path "J" in Figure 2.4.

Wastewater treatment can also contribute chlorides to soils. This is shown in paths "M" and "N" in Figure 2.4. Chlorides in wastewater originate from a variety of sources including salt used to recharge water softeners, salt used in home and industrial food preparation, salt excreted by people, and salt used in commercial and industrial processes that generate wastewater treated by public WWTPs or onsite wastewater treatment systems. Chloride may enter soils from wastewater through several means. Some WWTPs discharge their effluent to infiltration ponds. From these ponds, water containing chloride can infiltrate into soils, ultimately reaching groundwater. Similarly, onsite systems typically discharge their effluent into an infiltration field or mound within or on top of the soil. Chlorides from wastewater treatment can also enter soils through land application of septage and WWTP biosolids.

Chlorides can be deposited on soils from the atmosphere. This is shown in path "R" in Figure 2.4. On a continental level, most of these chlorides originate as salts in the ocean mobilized to the atmosphere through processes like wave action and spray. The amount of chloride deposited from the atmosphere is highest near the oceans and decreases with distance from the sea. Chloride from the atmosphere can be deposited on the land surface through two processes. Wet deposition occurs when chloride in the atmosphere mixes with suspended water and is removed through rain, snow, or fog. Annual rates of wet deposition of chloride in southeastern Wisconsin have been estimated at 0.21 to 0.51 kilograms per acre (kg per acre).[24] Dry deposition occurs when aerosols or dusts containing chlorides settle out of the atmosphere. Annual rates of dry deposition of chloride in southeastern Wisconsin have been estimated at 0.02 to 0.1 kg per acre.[25] While contributions of chloride to soil through atmospheric deposition appear to be relatively small on a regional scale, atmospheric contributions may generate impacts on a local scale. For example, visible injuries to woody plant tissues near roads tend to occur more often and be more severe on the downwind side of the roads. While aerial deposition of chlorides has been reported to occur up to about 1,640 feet from roads, deposition typically falls to the background levels seen in areas away from roads at about 130 to 330 feet from the edge of the pavement.[26]

Chlorides can be applied to soils through irrigation of agricultural fields and watering of lawns. This is shown in paths "Y" and "T" in Figure 2.4. The water used for this would originate from either groundwater or surface water, either through municipal water systems or through self-supplied withdrawals. The chloride contained in this water would be transferred to soils. The U.S. Geological Survey (USGS) estimated that in 2015 approximately 12,200 acres or almost two percent of the agricultural land in the Region were irrigated in the seven counties in southeastern Wisconsin, with an average application of 9.5 million gallons per day (mgd).[27]

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[20] Ibid.

[21] *J.P. Zublena, J.C. Barker, and D.P. Wessen,* Soil Facts: Dairy Manure as a Fertilizer Source, *North Carolina State University Agricultural Extension Service Publication AG-439-28 WQWM-122, 2012.*

[22] *K.L. Wells,* The Agronomics of Manure Use for Crop Production, *University of Kentucky Cooperative Extension Service Report AGR-165, 2014.*

[23] *U.S. Department of Agriculture National Agricultural Statistics Service 2019,* op. cit.

[24] *National Atmospheric Deposition Program,* 2020 Annual Summary, *October 2021.*

[25] Ibid.

[26] *L. Backman and L. Folkerson,* The Influence of Deicing Salt on Vegetation, Groundwater and Soil along Highway's E20 and 48 in Skaraborg County during 1998, *Swedish National Road and Transport Research Institute Publication No. VTI Meddelande 775A, 1995; Kelsey and Hootman 1992,* op. cit.

[27] *U.S. Geological Survey,* USGS Water Use Data for Wisconsin: 1985-2015, *waterdata.usgs.gov/wi/nwis/wu, accessed June 8, 2022.*

Finally, chlorides contained in or on vegetation can be deposited on soils during decomposition. This is shown in path "Z" in Figure 2.4. Plants require small amounts of chloride for growth. Adequate tissue concentrations of chloride are typically around 100 mg/kg.[28] When the above-ground portion of plants die or leaves fall from deciduous trees in the autumn, the chloride that they contain are transferred to the soil as they decompose.

Movement and Retention of Chloride in Soil

Chloride is generally considered to be inert in soil and has often been used as a tracer of groundwater movement. Recent studies suggest that substantial retention and/or release of chloride may occur in some soils.[29] This retention and release has been attributed to several processes including water and chloride moving vertically through soils at different rates depending on small-scale variations in soil structure and composition[30] and chloride uptake by vegetation.[31]

Tracer experiments using a radioactive isotope of chloride showed that short-term uptake and release of chloride by soil microbes and longer-term formation of chlorinated organic matter can result in retention and release of chloride by soils.[32] Extensive microbial uptake of chloride was found to occur over short time scales with about 24 percent of the initially available chloride in soil pore water being retained as part of microbial biomass within about one week. Most of this chloride was released to pore water within about one month. Under stable environmental conditions, the amount of chloride taken up by microbes in a natural soil would likely be about equal to the amount being released; however, changes in environmental conditions could result in an increase in uptake or release. Those changes that promote microbial growth would likely spur chloride uptake resulting in greater retention of chloride in soil. Conversely, those changes that promote microbial die-off would likely result in release of chloride to soil.

The same tracer experiments also found that chloride was retained through the natural formation of chlorinated organic matter.[33] This occurred more slowly than microbial uptake. After about 133 days, about 4 percent of the initially available chloride had been incorporated into chlorinated organic matter. The rate of formation was greatest between 35 and 70 days after addition of the tracer. It is not clear whether the formation of these compounds is biologically mediated.

Effects of Chloride Salts on Soil Structure

Components of Soil

Soil consists of four basic components: mineral material, humus, air, and water. Mineral material consists of broken and chemically weathered rock. It constitutes about 45 percent of the volume of soil.[34] Humus or organic material consists of partially decomposed matter derived from living organisms including leaves, plants, and animal droppings and it constitutes about 5 percent of the volume of soil. Air and water each constitute about 25 percent of the volume of soil, and both are needed by plant roots and soil organisms. The proportions of these components can vary with the type of soil and weather conditions.

Mineral particles in soil are present in a wide range of sizes. These sizes are grouped into three classes. From largest to smallest, these soil classes consist of sand, silt, and clay. While the composition of sand and silt is similar to the rock that they are derived from, the composition of clay is highly altered by chemical

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[28] *Cain et al. 2000,* op. cit.

[29] *See, for example, D. Bastviken, P Sandén, T. Svennson, C. Ståhlberg, M. Magounakis, and G. Öberg, "Chloride Retention and Release in a Boreal Forest Soil—Effects of Soil Water Residence Time and Nitrogen and Chloride Loads,"* Environmental Science & Technology, *40:2,977-2,982, 2006.*

[30] *M. Larrson and N. Jarvis, "Evaluation of a Dual-Porisity Model to Predict Field-Scale Solute Transport in a Macroporous Soil,"* Journal of Hydrology, *215:153-171, 1999.*

[31] *G.E. Likens,* Biochemistry of a Forested Ecosystem, *Springer-Verlag, 1995.*

[32] *D. Bastviken, F. Thomsen, T. Svensson, S. Karlsson, P. Sandén, G. Shaw, M. Matucha, and G. Öberg, "Chloride Retention in a Forest Soil by Microbial Uptake and by Natural Chlorination of Organic Matter,"* Geochimica and Cosmochimica Acta, *71:3,182-3,192, 2007.*

[33] Ibid.

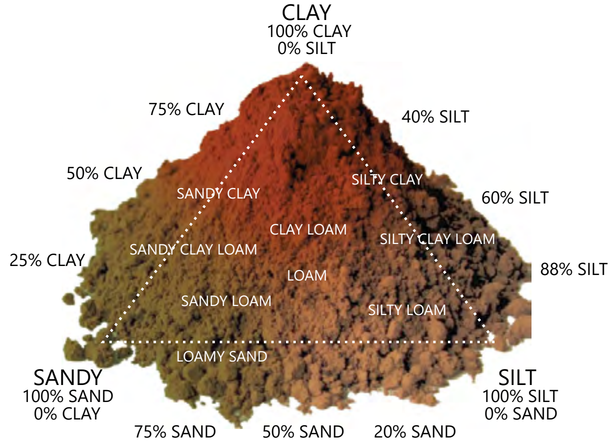
[34] *M.I. Harpstead, F.D. Hole, and W.F. Bennett,* Soil Science Simplified, *Iowa State University Press, Ames, Iowa, 1988.*

weathering. Clay particles are very small; the diameter of a clay particle is typically less than one one-thousandth of the diameter of a sand particle. The mineral components of soil and how they combine to form different soil types are shown in Figure 2.5.

Soil Structure

Soil structure consists of the arrangement of soil particles and the pore space between them. This is determined by how soil particles clump together and is the result of interactions among the particles. Sand and silt particles in soil are typically surrounded by a film of clay particles. The surfaces of clay particles and humus carry negative electrical charges. They will attract and electrostatically bind positively charged ions in soil pore water. Cations with more than one positive charge, such as calcium (Ca^{2+}), magnesium (Mg^{2+}) and aluminum (Al^{3+}) bond to negatively charged clay and humus particles. As shown in the top diagram in Figure 2.6, this creates bridges between clay particles linking them together. This creates a network in which silt and sand particles are clustered into soil aggregates of various sizes and shapes.

Figure 2.5
Mineral Components of Soil and How They Combine to Form Soil Types



Source: U.S. Department of Energy

Soil with good structure has many interconnected pore spaces that are occupied by air and water. These pores also provide space for the growth of plant roots and fungal filaments. Macropores are pores with a diameter greater than about 0.003 inch. These allow easy movement of water and air, drain freely by gravity, and provide habitat for soil organisms and plant roots. Smaller pores in the soil are referred to as micropores.

Degradation of Soil Structure by Salts

While positively charged ions are bound to the surfaces of clay and humus particles, they can be exchanged with other positively charged ions in the surrounding soil water. This is especially likely to occur when some cation is present at a relatively high concentration in soil water. Applications of salts to soil can increase the occurrence of this cation exchange. Sodium ions (Na^{+}) are effective at competing for negatively charged sites on clay and humus particles.[35] When the salt applied is sodium chloride, this can lead to replacement of divalent and multivalent cations such as Ca^{2+}, Mg^{2+}, and Al^{3+} by Na^{+}. This is shown in Figure 2.7. The amount of this displacement will increase as the concentration of Na^{+} increases.

Application of sodium chloride has chemical effects on the soil. The sodium ions will tend to accumulate in the soil, while the chloride ions will pass through with water, ultimately passing into surface or groundwater.[36] The presence of sodium ions can also lead to release of other cations from the soil. Experimental studies found consistent release of Mg^{2+}, Ca^{2+}, and potassium (K^{+}) as a result of sodium chloride addition.[37] Additional studies also found that sodium chloride additions to soil can result in release of iron (Fe^{2+}) and ammonium (NH_4^{+}).[38] As water flows through the soil, these released elements may leach out. Since many of these cations are essential nutrients for plants, this loss can reduce soil fertility.

[35] *S.E.G. Findlay and V.R. Kelly, "Emerging Indirect and Long-Term Road Salt Effects on Ecosystems,"* Annals of the New York Academy of Sciences, *1,223:58-68, 2011.*

[36] *D.M. Ramakrishna and T. Viraraghavan 2005,* op. cit.

[37] *S. Haq, S.S. Kaushal, and S. Duan, "Episodic Salinization and Freshwater Salinization Syndrome Mobilize Base Cations, Carbon, and Nutrients to Streams across Urban Regions,"* Biogeochemistry, *141:463-486, 2018.*

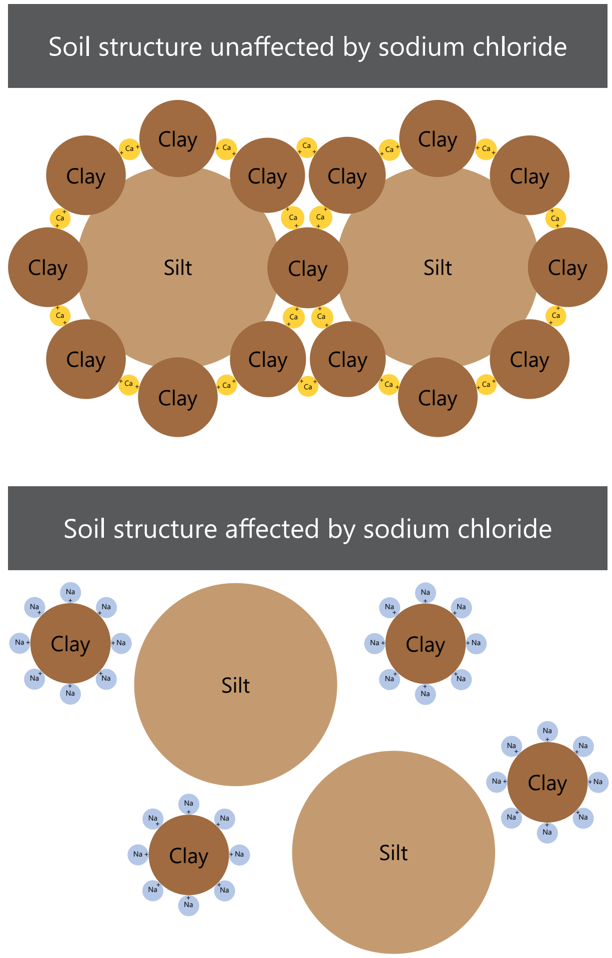
[38] *M. Cañedo-Argüelles, B.J. Kefford, C. Piscart, N. Prat, R.B. Schäfer, and C.J. Schulz, "Salinization of Rivers: An Urgent Ecological Issue,"* Environmental Pollution, *173:157-167, 2013.*

Application of sodium chloride also has physical effects that degrade the structure of soil. This happens because sodium ions carry only one positive charge. While many sodium ions can bind to a particular clay or humus particle, each sodium ion can bond to only one exchange site on a particle. Because of this, they are unable to form bridges linking clay particles together. This is shown in the lower diagram in Figure 2.6. Differences in the water of hydration associated with Na^+ ions versus the water of hydration associated with Ca^{2+} or Mg^{2+} ions cause disaggregation of the particles.

Applications of sodium chloride to soil will result in cation exchange that releases clay and silt particles from the network that forms soil aggregates. These particles will then clog the micropores. This release also reduces the size of soil aggregates which reduces the number and size of soil pores. Loss of soil pores can result in soil compaction that can reduce the permeability of the soil to air and water.[39] Compaction and reduction in soil aggregates can lead to several other impacts including reduced infiltration, reduced water retention, reduced water and nutrient availability to plants, reduced root penetration, formation of crusts on the soil surface, and reduced emergence of seedlings. These impacts can reduce the suitability of a soil for plant growth. A comparison of good soil structure to poor soil structure is shown in Figure 2.8. Soil with better structure is shown on the left and poor soil structure is shown on the right of the figure.

Addition of enough sodium to soil can create a strong alkali condition.[40] An alkaline environment can dissolve humus in the soil. It also results in the formation of a dark crust on the soil surface when water evaporates. Plants grown under alkaline conditions will show drought-related injuries.

Figure 2.6
Basic Units of Soil Structure Unaffected and Affected by Sodium Chloride



Source: SEWRPC

The extent to which these soil impacts occur in response to application of sodium from salts may depend on the nature of the parent material from which a soil is derived. Soils derived from calcium-rich rock may be less vulnerable to displacement of Ca^{2+} by Na^+ because higher concentrations of sodium are needed to displace calcium in these types of soils.[41] Such resistance would be accompanied by sodium ions being more mobile in the water in calcium-rich soils than other soils, potentially making nearby surface and groundwater more prone to sodium pollution.

Mobilization of Metals and Other Materials

Application of chloride salts, whether through direct application or runoff, can promote the release of heavy metals from soils and sediment. Heavy metals are a group of metals and metalloids that can have adverse biological effects. Some are essential nutrients to at least some organisms in small amounts but can be toxic at higher concentrations or in certain chemical forms. Examples of these include cobalt, iron, and zinc. Other heavy metals, such as cadmium, mercury, or lead, have no biological function and are highly toxic.

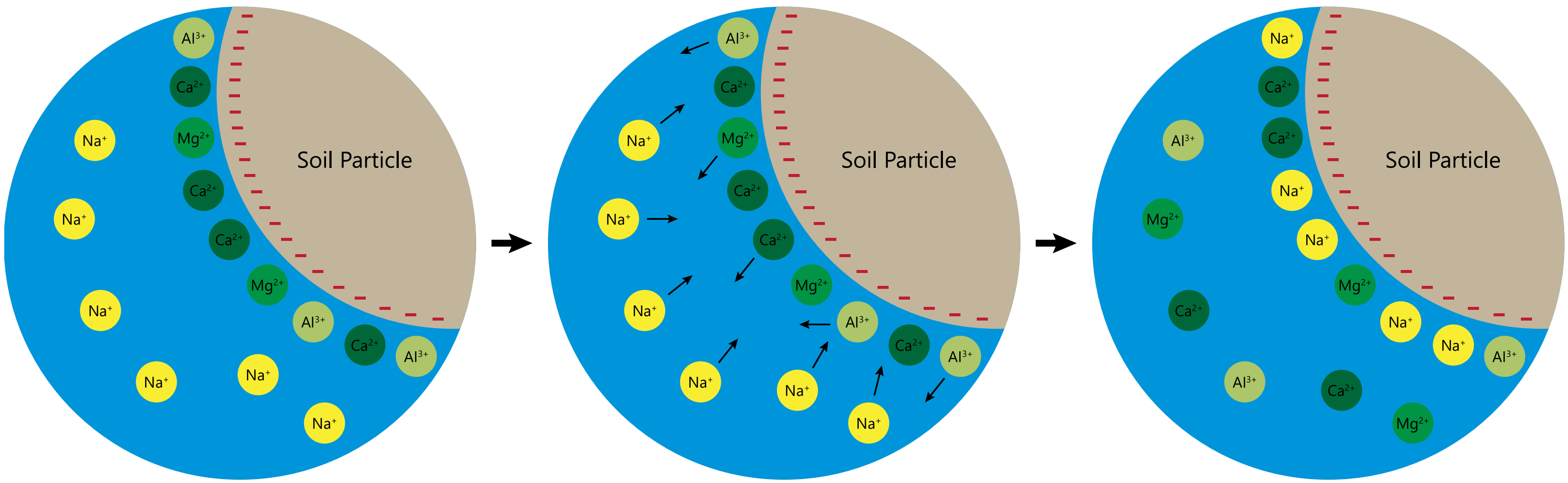
[39] *A.C. Norrstrom and E.G. Bergstedt, "The impact of Road De-Icing Salts (NaCl) on Colloidal Dispersion and Base Cation Pools in Roadside Soils,"* Water, Air, and Soil Pollution, *127:291-299, 2001.*

[40] *M.I. Harpstead, F.D. Hole, and W.F. Bennett 1988,* op. cit.

[41] *M.C. Eimers, K.N. Croucher, S.M. Raney, and M.L. Morris, "Sodium Accumulation in Calcareous Roadside Soils,"* Urban Ecosystems, *18:1,213-1,225, 2015.*

Figure 2.7
Displacement of Cations by Sodium in Soil and Sediment

When sodium ions (Na^+) are common in soil water, they can displace other cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and aluminum (Al^{3+}) that are bound to clay and humus particles.



Source: SEWRPC

Heavy metals often accumulate in roadside soils, especially soils with high organic content.[42] This is due, in part, to the fact that heavy metal ions readily bond to organic materials. The most commonly found metals in roadside soils include aluminum, boron, cadmium, copper, iron, lead, manganese, mercury, titanium, and zinc.[43] Automobile traffic is the major source of these metals to roadside soils. This results from rusting of vehicles; wear and tear of engine parts, brakes, and tires; leaking fluids; and the legacy effects of leaded gasoline.[44] Other heavy metal sources to soils may include shingles and sidings of buildings,[45] industrial activities, and burning of fossil fuels. Examples of sources of heavy metals to the environment are shown in Figure 2.9. Specific sources of metals to soils near roadways include:

Figure 2.8
A Comparison of Good and Poor Soil Structure

Source: Wikimedia Commons

- Cadmium from diesel oil and tire wear
- Chromium from metal plating and brake lining wear
- Copper from metal plating and wear of bearings and brake linings
- Iron from vehicle rust, highway structures, and engine wear
- Lead from wear of bearings and brake linings, lubricating oils, and grease
- Zinc from tire wear, motor oil, and grease[46]

Concentrations of heavy metals in roadside soils can vary depending on the number of vehicles using the road, the time since the road was built, and the types of soils along the road.[47] Concentrations of heavy metals in soils are typically highest within about 30 feet of the paved surface and within the top six inches of soil.[48] Movement of heavy metals away from roads depends on the metal, the permeability of the road surface, and climatic factors such as the season and amount of precipitation.[49]

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[42] *N.S. Bolan and V.P. Duraisamy, "Role of Inorganic and Organic Soil Amendments on Immobilization and Phytoavailibilty of Heavy Metals: A Review Involving Specific Case Studies,"* Soil Research, *41:533-555, 2003.*

[43] *S.C. Trombulak and C.A. Frissell, "Review of Ecological Effects of Roads on Terrestrial and Aquatic Communities,"* Conservation Biology, *14:18-30, 2000.*

[44] *C. Amrhein, J.E. Strong, and P.A. Mosher, "Effect of Deicing Salts on Metal and Organic Matter Mobilization in Roadside Soils,"* Environmental Science and Technology, *26:703-709, 1992; A.P. Davis, M. Shokouhian, and S. Ni, "Loading Estimates of Lead, Copper, Cadmium, and Zinc in Urban Runoff from Specific Sources,"* Chemosphere, *44:997-1,009, 2001.*

[45] *Davis, Shokouhian, and Ni 2001,* op. cit.

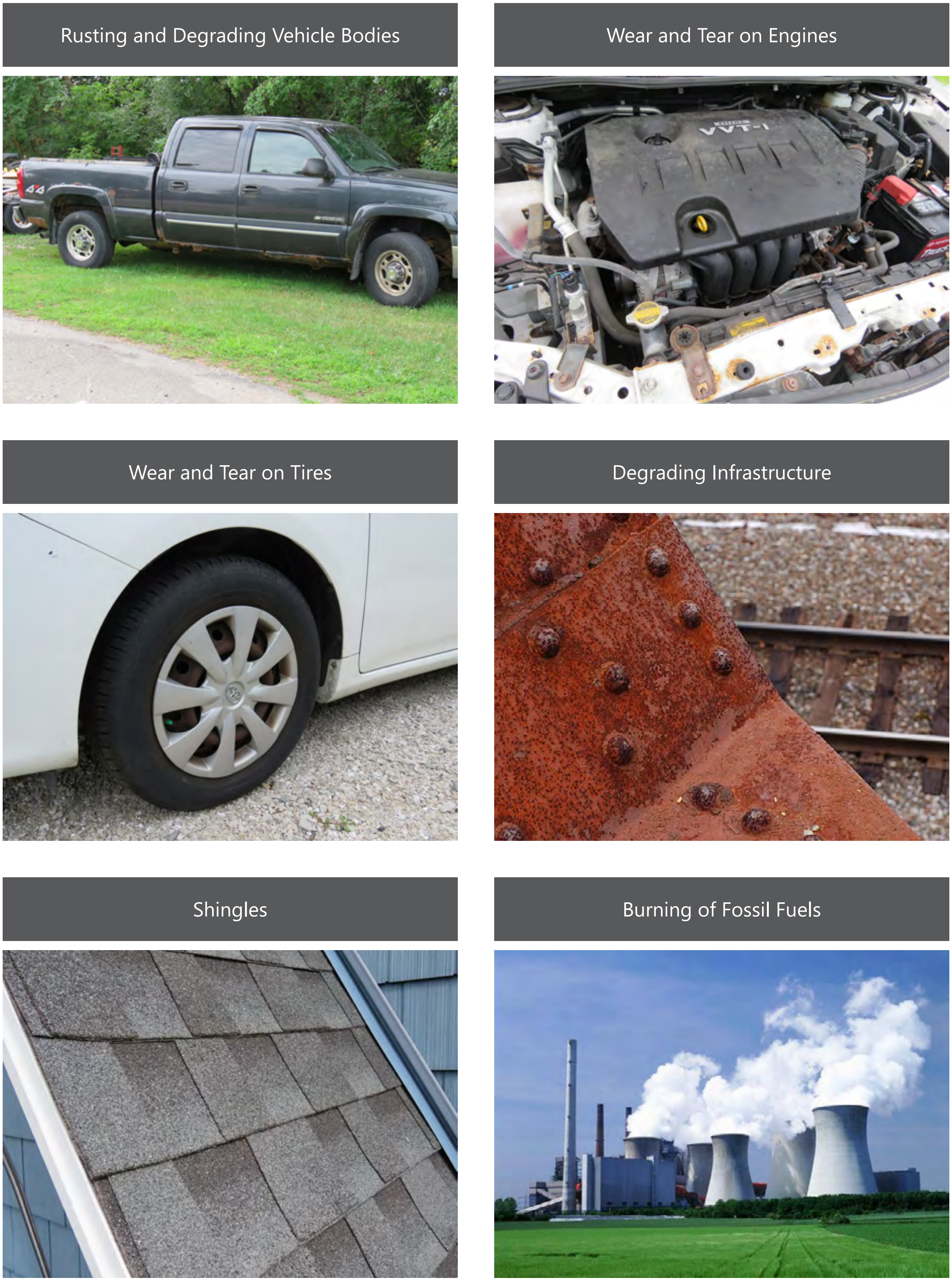
[46] *National Cooperative Highway Research Program,* Guidelines for the Selection of Snow an Ice Control Materials to Mitigate Environmental Impacts, *NCHRP Report No. 577, 2007.*

[47] *M. Saeedi, M. Hosseinzadeh, A. Jamshidi, and S.P. Pajooheshfar, "Assessment of Heavy Metals Contamination and Leaching Characteristics In Highway Side Soils, Iran,"* Environmental Monitoring and Assessment, *151:231-241, 2009; B. Wei and L. Yang, "A Review of Heavy Metal Contaminations in Urban Soils, Urban Road Dusts and Agricultural Soils from China,"* Microchemical Journal, *94:99-107, 2010.*

[48] *M. Werkenthin, B. Kluge, and G. Wesolek, "Metals in European Roadside Soils and Soil Solution: A Review,"* Environmental Pollution, *189:98-110, 2014.*

[49] *P. Göbel, C. Dierkes, and W.G. Coldewey, "Storm Water Runoff Concentration Matrix for Urban Areas,"* Journal of Contaminant Hydrology, *91:26-42, 2007.*

Figure 2.9
Examples of Sources of Heavy Metals to the Environment



Source: Wikimedia Commons and SEWRPC

Heavy metals in soil and sediment can be present in a variety of chemical forms. These forms differ in how readily they may be released and how available they are to affect organisms in the soil. Readily available forms include free ions, easily exchangeable ions associated with clay and humus particles, ions adsorbed to particles, or ions complexed with labile organic compounds or other inorganic ions. Less available heavy metal forms in the soil and sediment include metal ions incorporated into crystal structures or refractory organic complexes. Metals can be transformed from one form to another. For example, metals that are incorporated into the crystal structures of minerals are typically not readily available; however, changes in soil chemistry can allow them to move from a mineral state to a soluble ion, or adsorbed ion, or incorporate them into a chemically complexed state with compounds such as organic molecules, releasing them from the crystal structure.[50]

Mechanisms of Heavy Metal Release from Soil Due to Salt Application

Road salts can release heavy metals from soils through several related mechanisms including disrupting soil structure, changing soil chemistry, and altering ion exchange in the soil.[51]

As previously discussed, high concentrations of sodium ions can disrupt soil structure. This can cause colloidal structures in soil to break down, leading to the formation of chloride-metal complexes with heavy metals.[52] These complexes increase the solubility of the metals and mobilize them into soil pore water.[53] This mobilization is partially dependent on the organic content of the soil.[54]

In some soil types, salts may also change soil chemistry in ways that promote the release of heavy metals. Cation exchange of Na^+ ions for hydrogen ions (H^+) might lower pH. Since the solubility of metals tends to increase with decreasing pH, the addition of salt can promote heavy metal release. This effect may not be particularly strong and will depend on soil type. Any effect of this type would be more likely to occur in clay soils or organic rich sediments than in sandy or carbonate soils, as more cation exchange sites are present in the former types of soils.

Cations from salts can also directly displace metals bound to humus because the binding affinity of many organic compounds is higher for sodium, calcium, and magnesium ions than it is for heavy metal ions.[55] Magnesium and calcium ions tend to be better at displacing other cations than sodium, so applications of magnesium chloride or calcium chloride are more likely to mobilize heavy metals in soils and sediments through ion exchange than applications of sodium chloride.[56] In addition, since a single molecule of magnesium chloride or calcium chloride has a greater number of chloride ions than one of sodium chloride, these salts could potentially mobilize more heavy metals than sodium chloride through greater formation of chloride-metal complexes.[57]

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[50] *P.G.C. Campbell and P.M. Stokes, "Acidification and Toxicity of Metals to Aquatic Biota,"* Canadian Journal of Fisheries and Aquatic Sciences, I42:2,034-2,049, 1985.

[51] *Norrstrom and Bergsted 2001,* op. cit.

[52] *A colloid consists of a mixture of microscopic insoluble particles that are suspended in some other substance. Typically, the size of the suspended particles is between 0.001 and 10 micrometers. Examples of colloids include mayonnaise, fog, milk, and toothpaste.*

[53] *J.L. Howard and J.E. Sova, "Sequential Extraction Analysis of Lead in Michigan Roadside Soils: Mobilization in the Vadose Zone by Deicing Salts?"* Soil and Sediment Contamination, *2:361-378, 1993; M. Bäckström, S. Karlsson, L. Bäckman, L. Folkeson, and B. Lind, "Mobilisation of Heavy Metals by Deicing Salts in a Roadside Environment,"* Water Research, *38: 720-732, 2004.*

[54] *D.G. Lumsdon, L.J. Evans, and K.A. Bolton, "The Influence of pH and Chloride on the Retention of Cadmium, Lead, Mercury, and Zinc by Soils,"* Soil and Sediment Contamination, *4:137-150, 1995.*

[55] *Bäckström, Karlsson, Bäckman, Folkeson, and Lind 2004,* op. cit.

[56] *J.A. Acosta, B. Jansen, K. Kalbitz, A. Faz, and S. Martínez-Martínez, "Salinity Increases Mobility of Heavy Metals in Soils,"* Chemosphere, *85:1,318-1,324, 2011.*

[57] *M.S. Schuler, W.D. Hintz, D.K. Jones, L.A. Lind, B.M. Mattes, A.B. Stoler, K.A. Sudol, and R.A. Relyea, "How Common Road Salts and Organic Additives Alter Freshwater Food Webs: In Search of Safer Alternatives,"* Journal of Applied Ecology, *doi: 10.1111/1365-2664,12877, 2017.*

Most of the mobilization of heavy metals by salts is probably due to ion exchange rather than changes to soil structure or pH.[58] The importance of ion exchange in mobilizing heavy metals depends on several factors. Some heavy metals are more susceptible to mobilization from soils than others. For example, cadmium, cobalt, and copper are more easily released through soil ion exchange than lead or zinc.[59] Similarly, chromium is less likely to be mobilized by soil ion exchange than other metals.[60] The type of salt also influences heavy metal mobilization. As discussed previously, application of magnesium chloride and calcium chloride is more likely to mobilize heavy metals from soil than sodium chloride. The composition and structure of the soil also affect heavy metal mobilization.[61] For example, wetland soils often become anoxic, especially when inundated. Anaerobic respiration in these soils can increase the rate of conversion of heavy metals bound in soil to more available forms.[62]

Impacts of Heavy Metal Mobilization by Salts

Release of heavy metals by chloride salts can alter their distribution in soils and affect the amounts that are bioavailable in soil and freshwater. This can have several impacts on other ecological systems and a few examples are given below.

In streams, contamination with heavy metals, especially copper and zinc, can inhibit some microbial activity. This occurs as reductions in both the rate of microbial respiration and the rate at which leaf litter is broken down.[63] This reduces the rate at which food becomes available to macroinvertebrates, reducing the growth of their populations and potentially limiting the overall production of organisms that depend on them as a food source.

Wetlands often serve as sinks for heavy metals. This is due both to the high organic content of wetland soils and the abilities of some wetland plants and microorganisms to tolerate these metals and accumulate them in their tissues.[64] Contamination of wetlands with chloride salts could potentially release these metals and allow them to contaminate connected groundwater or surface water systems. In addition, the abundance of metals, especially nickel, regulates the production of methane and other greenhouse gases in wetlands.[65] This occurs because the enzyme that methanogenic bacteria use to produce methane requires ionic nickel in the form of Ni^{+2} as a cofactor.[66] Mobilization of nickel ions due to the application of salt can thus increase production of methane in wetlands which contributes to greenhouse gas emissions linked to climate change.

Mobilization of heavy metals from soil by chloride salts could lead to increased concentrations of these metals in organisms. Heavy metals tend to accumulate in the tissues of organisms and can be magnified as they pass through the food web, with higher concentrations being found in the tissues of organisms that are at higher trophic levels such as predatory fish. In addition, this chloride salt mobilization could increase the toxic effects of heavy metals as they enter the food web. This potential has not been studied.[67]

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[58] *Bäckström, Karlsson, Bäckman, Folkeson, and Lind 2004,* op. cit.

[59] Ibid.

[60] *C. Pagotto, N. Remy, M. Legret, and P. Le Cloirec, "Heavy Metal Pollution of Road Dust and Roadside Soil Near a Major Rural Highway,"* Environmental Technology, *22:307-319, 2001.*

[61] *M.S. Schuler and R.A. Relyea, "A Review of the Combined Threats of Road Salts and Heavy Metals to Freshwater Systems,"* BioScience, *68:327-335, 2018.*

[62] *S.Y. Kim and C. Koretsky, "Effects of Road Salt Deicers on Sediment Biogeochemistry,"* Biogeochemistry, *112:343-358, 2013.*

[63] *D.M. Carlisle and W.H. Clements, "Leaf Litter Breakdown, Microbial Respiration and Shredder Production in Metal-Polluted Streams,"* Freshwater Biology, *50:380-390, 2005; V. Ferreira, J. Koricheva, S. Duarte, D.K. Niyogi, and F. Guérold, "Effects of Anthropogenic Heavy Metal Contamination on Litter Decomposition in Streams: A Meta-Analysis,"* Environmental Pollution, *210:261-270, 2016.*

[64] *I. Spellerberg, "Ecological Effects of Roads and Traffic: A Literature Review,"* Global Ecology and Biogeography Letters, *7:317-333, 1998.*

[65] *N. Basilko, and J.B. Yavitt, "Influence of Ni, Co, Fe, and Na Additions on Methane Production in Sphagnum-Dominated North American Peatlands,"* Biogeochemistry, *52:133-153, 2001.*

[66] *D.H. Rothman, G.P. Fournier, K.L. French, E.J. Alm, E.A. Boyle, C. Cao, and R.E. Summons, "Methanogenic Burse in the End-Permion Carbon Cycle,"* Proceedings of the National Academy of Sciences, *111:5,462-5,467, 2014.*

[67] *Schuler and Relyea 2018,* op. cit.

Finally, both chloride salts and heavy metals are toxic to organisms, especially those dwelling in freshwater. There have been few studies of how their toxicities interact; however, there is the potential that their combined toxicity may be greater than that of either one alone. This was suggested in a study of salmon egg development that found that the combined effects of road salt and heavy metals were more severe than would have been predicted based on the effects of each alone.[68] However, the study acknowledged that more research needs to be done on this topic.

2.4 IMPACTS OF CHLORIDE ON GROUNDWATER

General Groundwater Principles

Groundwater includes water that has percolated into the earth and has reached areas of saturation below the Earth's surface. The elevation of the shallowest saturated subsurface water-bearing media is commonly referred to as the "water table". Groundwater is not visible to casual observation except where it discharges to surface water as springs and seeps. Water in unsaturated soil above the water table can either return to the atmosphere via evapotranspiration or may move downward to join groundwater if soil moisture increases through additional percolation from the surface.

In southeastern Wisconsin, local precipitation is the source of most groundwater and groundwater is stored in and moves through the natural pore spaces and fractures found in unconsolidated sediment and bedrock. Sediment and rock units with significant porosity or fracturing can store large amounts of water. These units can supply useable amounts of water over prolonged periods and are referred to as "aquifers." Figure 2.10 shows that three main aquifers underlie southeastern Wisconsin. They are described below in order of increasing depth from the land surface.

- **Sand and gravel aquifer:** This aquifer is primarily found in porous, coarse-grained sand and gravel deposited by glacial action. Much of the water feeding this aquifer infiltrates through the land surface in the local area. Its thickness and properties vary widely, but it is an important source of local water supply for many portions of the Southeastern Wisconsin Region. It is commonly highly vulnerable to contamination and over exploitation. The quality and quantity of water in this aquifer can be significantly influenced by changes in local land use. The sand and gravel aquifer is generally in good hydraulic communication with the underlying dolomite aquifer. This aquifer is critical for contributing baseflows to streams, rivers, lakes, and wetlands.

- **Dolomite aquifer:** Water in this aquifer is stored in and moves primarily through fractures in the bedrock. Much of the water found in this aquifer is derived from local infiltration. Although its water-bearing characteristics and thickness vary widely, it is a very important water supply aquifer. When located under a relatively thick layer of unconsolidated sediment, it is somewhat less vulnerable to contamination and overexploitation.

- **Sandstone aquifer:** The sandstone aquifer is commonly deeply buried and is found at depths well below the sand and gravel and dolomite aquifers. Water is stored in and moves through the rock's innate porosity and fractures in the rock. This aquifer is very thick, but the water bearing characteristics vary widely with depth. A layer of low permeability Maquoketa shale that overlies the sandstone aquifer extends over the eastern portion of the Southeastern Wisconsin Region. This shale separates the sandstone aquifer from the dolomite and sand and gravel aquifers that lie above it and prevents water from percolating into the sandstone aquifer. Water recharging the sandstone aquifer infiltrates through the shallow sand and gravel and dolomite aquifers in western portions and to the west of the Region. While the sandstone aquifer is less vulnerable to pollution sources in areas where the Maquoketa shale is present, it is somewhat more vulnerable to contamination in its recharge area where it is hydrologically connected to the surface. The sandstone aquifer is an important source of municipal and industrial water supply.

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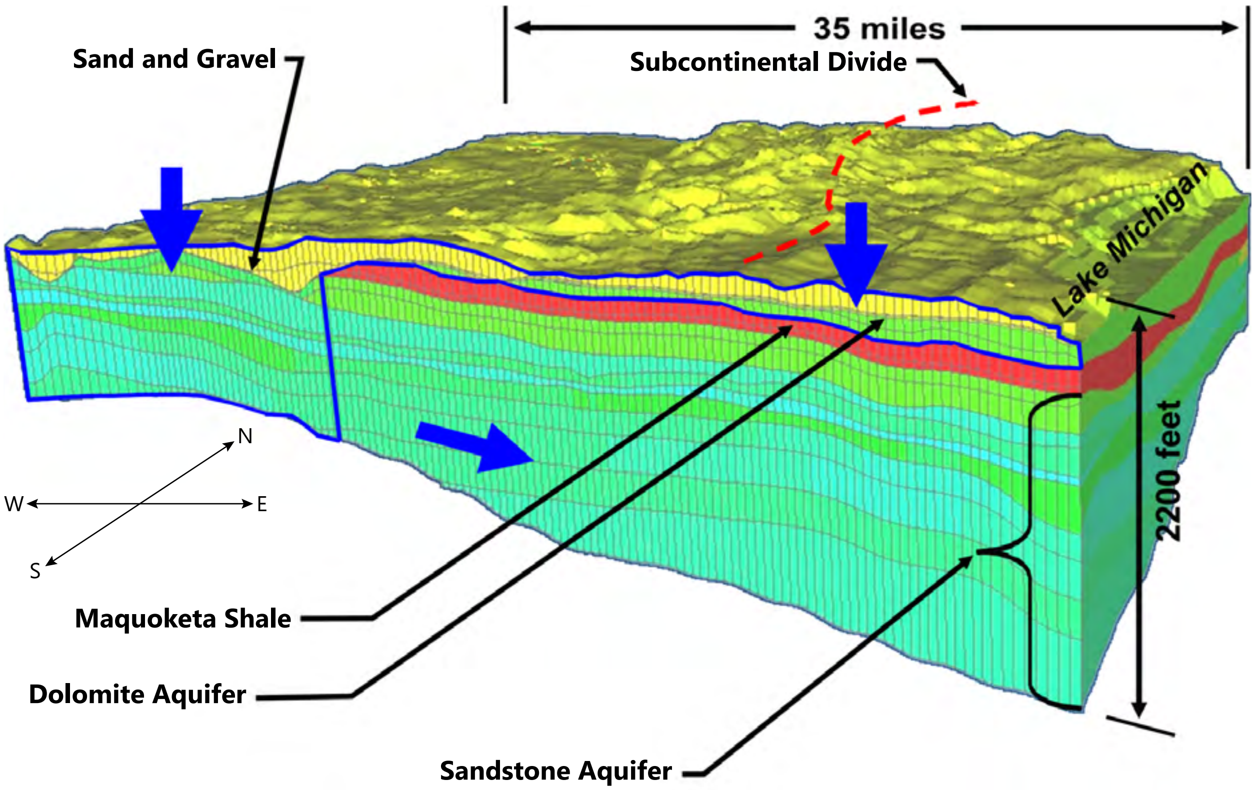
[68] *U. Mahrosh, M. Kleiven, S. Meland, B.O. Rosseland, B. Salbu, and H.C. Teien, "Toxicity of Road Deicing Salt (NaCl) and Copper (Cu) to Fertilization and Early Developmental Stages of Atlantic Salmon (*Salmo salar*),"* Journal of Hazardous Materials, *280:331-339, 2014.*

Figure 2.10
Aquifer Systems in Southeastern Wisconsin



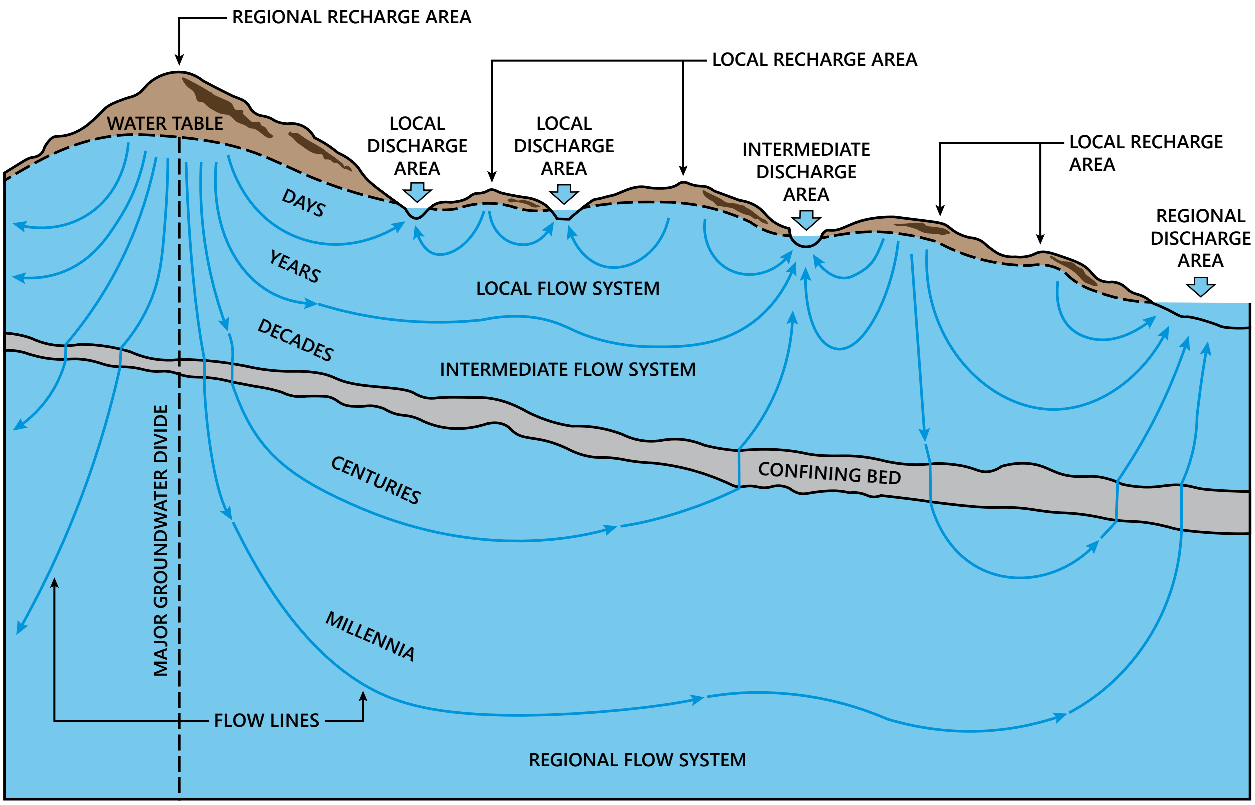
Source: U.S. Geological Survey

Groundwater Recharge, Movement, and Discharge

The flow of groundwater in the subsurface is a complex three-dimensional process determined by several factors, including precipitation, topography, soil permeability and structure, land use, and the lithology and water-bearing properties of rock units. Water enters groundwater flow systems in recharge areas and moves through them toward discharge areas. In recharge areas, the flow of groundwater is downward; in discharge areas, the flow is upward. Between these two areas, groundwater flow is essentially horizontal. The idealized concept of groundwater flow in profile given in Figure 2.11 shows groundwater moving from recharge areas to discharge areas. One of the most significant differences between recharge areas and discharge areas is that the areal extent of discharge areas is generally much smaller than that of recharge areas. Regional recharge occurs primarily in upland areas or topographic high points, but local recharge can occur anywhere. Discharge from aquifers occurs at low points in the land surface such as rivers and lakes, or to wells. Recharge areas, from which flow paths originate and diverge, are the locations of groundwater divides, across which there is no horizontal groundwater flow.

The pattern of groundwater flow from a recharge area to a discharge area constitutes a dynamic flow system, which incorporates several superimposed elements (see Figure 2.11). Depending on the drainage basin topography and the thickness of the aquifer system, groundwater flow systems may have local, intermediate, and regional components. If the surface topography has well-defined local relief, such as in many parts of the Region, a series of local shallow groundwater flow systems can form. If the aquifer systems are large and deep enough, deeper, intermediate, and regional flow systems may develop. There may be a series of local and intermediate flow systems between the regional recharge and discharge areas (see Figure 2.11). This idealized description of flow systems assumes steady-state flow, without extensive pumping of groundwater from deep wells. Groundwater flow systems can be altered both locally and regionally by well pumping.

Figure 2.11
Idealized Groundwater Flow Systems Under Steady State Conditions



Source: Modified from A. Zaporozec in SEWRPC Technical Report No. 37, Groundwater Resources of Southeastern Wisconsin, *2002*

The time it takes groundwater to move from a recharge area to a discharge area may range from a few days in the zone closest to the discharge area to thousands of years (millennia) for water that moves from the central part of a major recharge area through the deeper parts of the groundwater flow system. Flow paths that penetrate into the deepest portions of the aquifer system generally have the longest travel time from recharge to discharge areas (see Figure 2.11).

Much of the movement and discharge of groundwater in the Region occurs in local, unconfined, shallow flow systems within a few miles of points of recharge.[69] Depth of the local systems probably does not exceed 200 feet. Groundwater in semi-confined or confined aquifers moves in intermediate or regional flow systems within the bedrock, where the flow is deeper and slower, and crosses much longer distances from recharge areas to discharge points such as Lake Michigan or deep wells in the eastern part of the Region.

Groundwater sustains water levels and flow in lakes, wetlands, and perennial streams during dry weather. Groundwater systems also modulate flood flows by infiltrating water during wet weather. Groundwater that discharges to surface waterbodies is commonly referred to as "baseflow". Baseflow can either directly enter large waterbodies, or it can enter small streams, ponds, springs, and seeps tributary to larger waterbodies.

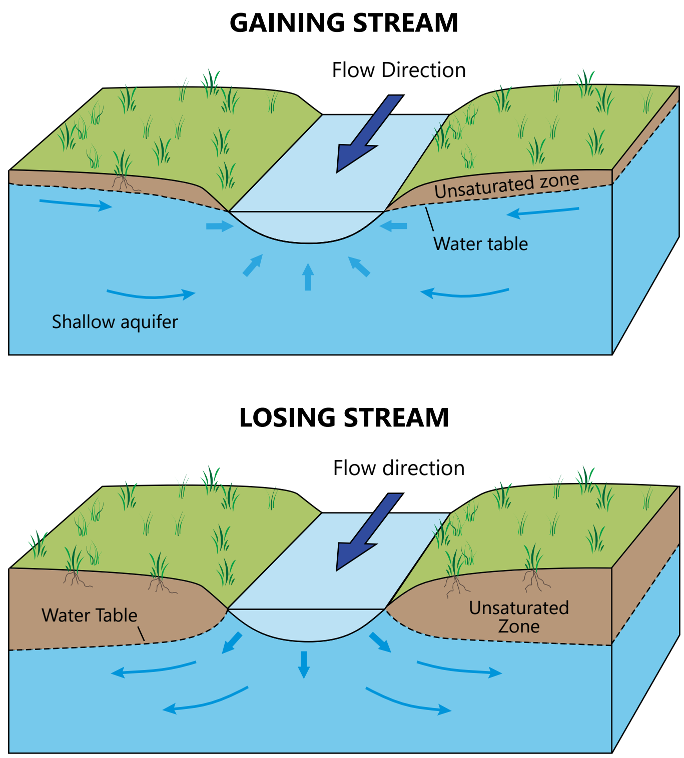
Baseflow sustains dry-weather lake elevation and the flow of perennial streams. Groundwater typically contains little to no sediment, has a more stable temperature regime, and commonly contains a lower overall pollutant load when compared to surface water runoff—all of which are favorable to aquatic life and the ecology of waterbodies. Groundwater-derived baseflow also helps maintain water elevations and/or flow in many lakes, wetlands, and streams during drier weather periods. Reliable water elevations and flow regimes enable groundwater-fed waterbodies to support a diverse assemblage of plants and animals. Groundwater is critical to these waterbodies' ability to provide unique ecological functions.

[69] *H.L. Young,* Summary of Ground-Water Hydrology of the Cambrian-Ordovician Aquifer System in the Northern Midwest, United States, *U.S. Geological Survey Professional Paper 1405-A, 1992.*

Groundwater supplies are generally replenished by precipitation soaking into the ground and entering aquifers. Water that infiltrates the land surface and enters aquifers is often referred to as "groundwater recharge." Precipitation is the source of essentially all groundwater recharge, but recharge does not necessarily occur uniformly throughout the landscape, at the point where precipitation initially strikes the Earth, or uniformly throughout the year. Relatively flat undeveloped areas underlain by thick layers of granular permeable mineral soil are generally able to contribute more water to groundwater recharge and are identified as having high or very high groundwater recharge potential. On the other hand, hilly areas underlain with low permeability soils such as clay soils and drained by storm sewers are more likely to have low recharge potential. Water running off from areas less conducive to groundwater recharge can still flow to areas more permeable and infiltrate there, becoming a component of groundwater flow. Most groundwater recharge occurs during periods of low natural water demand such as times when plants are dormant or when precipitation or runoff are abundant. Little groundwater recharge occurs from small summer rains, even on good recharge areas, because higher uptake by plants and greater evaporation rates associated with warmer temperatures consume the incident precipitation, returning it to the atmosphere.

The relationship between surface waterbodies and groundwater is complicated. Because the sand and gravel and dolomite aquifers are hydrologically connected to surface waterbodies, water can move both from groundwater to a surface waterbody and from a surface waterbody to groundwater. As shown in the "Gaining Stream" panel of Figure 2.12, a waterbody gains water when groundwater elevations are higher than the adjacent waterbody. Conversely, a perennial waterbody loses water wherever the water table elevation is lower than the waterbody's elevation. In such instances, water seeps into the underlying groundwater system (see Figure 2.12, "Losing Stream"). In some instances, such as ephemeral streams, the water table may not be in contact with the surface water feature. Stream reaches that receive groundwater discharge are called gaining reaches and those that lose water to the underlying aquifer are called losing reaches. The rate at which water flows between a stream and its adjoining aquifer depends on the hydraulic gradient between the two waterbodies and on the hydraulic conductivity of geologic materials that are located at the groundwater/surface-water interface. For example, a clayey streambed will reduce the rate of flow between a stream and the adjacent aquifer as compared to a sandy or gravelly streambed. In the absence of surface-water contributions, streamflow volume increases along gaining reaches and decreases along losing reaches. Streams along their length can have both gaining and losing reaches and the extent of these reaches may change based upon prevailing conditions. Since precipitation rates, evapotranspiration, water table elevations, and human-induced hydrologic stressors vary with time, a particular stream reach can switch from a gaining to a losing condition or from a losing to a gaining condition from one time period to the next.

Figure 2.12
Interactions of Surface Water and Groundwater



Source: Modified from T.C. Winter, J.W. Harvey, O.L. Franke, and W.M. Alley, Ground Water and Surface Water: A Single Resource, *U.S. Geological Survey Circular 1139, p. 9, 1998, and SEWRPC*

Movements of Contaminants in Groundwater

Contamination of groundwater occurs when pollutants enter an aquifer. Some of the routes through which contaminants enter reflect the process of groundwater recharge and the hydraulic connections between groundwater and surface waterbodies. Recharge can carry contaminants from runoff and the land's surface through the soil into aquifers. Similarly, the connections between surface waterbodies and groundwater means that movement of water from surface water into groundwater will tend to carry contaminants contained in the water into groundwater. The ability of a contaminant to travel through soil or sediment and enter an aquifer depends on the chemical compositions of the contaminant and the materials comprising the soil, sediment, and aquifer. Because of its high solubility and mobility, chloride will generally travel with the water.

Contaminants in groundwater will often form plumes moving away from the source of contamination. This is shown in Figure 2.13. The general direction of contaminant movement follows the main flow of groundwater. If that were the only process influencing contaminant movement, the flow would look roughly like a solid tube moving through the groundwater. Two other processes cause the plume to spread out from the main route of flow. First, diffusion results in contaminant molecules dispersing away from the main line of groundwater movement. Second, contaminant molecules will be carried away from their source by local eddies around particles in the aquifer and by fractures through the rock. These processes act simultaneously and are independent of the main flow path through the aquifer. When dispersion of a contaminant plume occurs, it tends to decrease the contaminant concentration along the direction of groundwater flow, but contamination affects an increasingly larger volume of the aquifer with increasing distance from the contaminant source.[70]

Different contaminants may move through groundwater at different rates. The movement of some contaminants may be retarded due to chemical interactions with the material making up the aquifer. The result of this is that the movement of these contaminants may be slower than the linear rate of groundwater movement.

Chloride ions will tend to move through groundwater at a rate near that of the groundwater movement. This is due to several properties of chloride ions including that they are highly soluble in water, they do not significantly participate in oxidation-reduction reactions, they are not readily adsorbed onto mineral surfaces, and they play few biochemical roles. Chloride ions tend to remain in solution through most processes that would remove other ions.[71] While they are highly mobile their movement in some compacted, fine-grained materials can be somewhat restricted by their relatively large size.

Sources of Chlorides to Groundwater

Chloride can reach groundwater through several routes. These pathways are illustrated and described in Figure 2.4 and Table 2.1.

Anthropogenic chloride entering groundwater generally comes through one of two paths. Chlorides on the land surface can be carried through the soil into groundwater in conjunction with groundwater recharge. This is shown as path "Q" in Figure 2.4. Similarly, movement of water from surface water into groundwater will carry chloride from the surface waterbody into groundwater. This is shown as path "U" in Figure 2.4. Chlorides originating from other sources generally pass through one or both paths in order to enter groundwater.

Deicing salts, for example, may follow paths "A," "J," and "Q" in Figure 2.4 from the truck through impervious surface and soil to groundwater. After being applied to impervious areas such as highways, some of this salt will be moved to soil adjacent to the highway either through plowing of salt-laden snow to the roadside or through salt-containing runoff flowing onto roadside soils. Additional salt may bounce or roll onto soil adjacent to the highway during deicing operations. The salt will then infiltrate through soils near the road into groundwater. A statewide groundwater mapping study in Connecticut found that chloride concentrations in groundwater varied with proximity to highways and that concentrations increased with the increase in road application rates.[72] Similarly, a study of groundwater chloride concentrations in domestic wells in Vermont found that groundwater in wells closer to a paved road had substantially higher chloride concentrations than concentrations in wells that were farther away.[73]

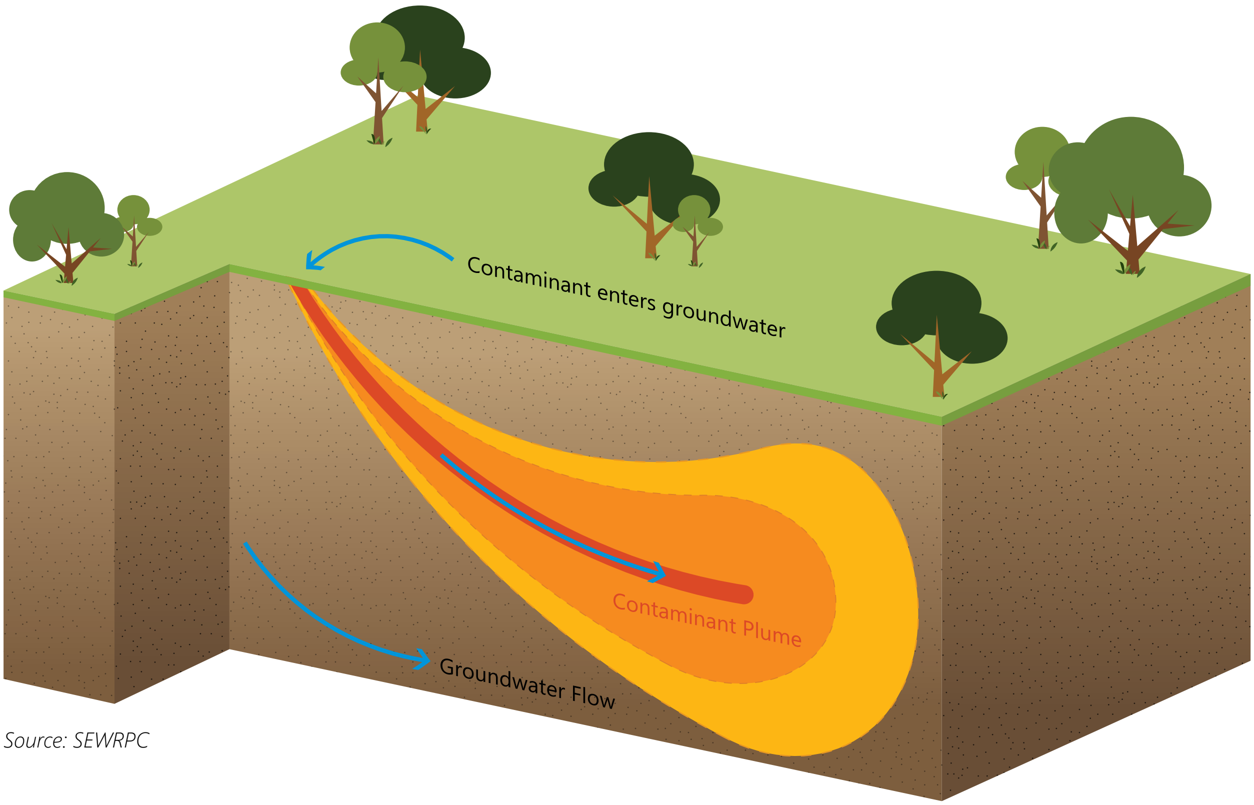
[70] *L.R. Watson, E.R. Bayless, P.M. Buszka, and J.T. Wilson,* Effects of Highway Deicer Application on Ground-Water Quality of the Calumet Aquifer, Northwest Indiana, *U.S. Geological Survey Water-Resources Investigations Report No. 01-4260, 2001.*

[71] *J.D. Hem,* Study and Interpretation of the Chemical Characteristics of Natural Water (Third Edition), *U.S. Geological Survey Water Supply Paper No. 2254, 1989.*

[72] *J.P. Cassanelli and G.A. Robbins, "Effects of Road Salt on Connecticut's Groundwater: A Statewide Centennial Perspective,"* Journal of Environmental Quality, *42:737-748, 2013.*

[73] *J.P. Levitt and S.L. Larsen,* Groundwater Chloride Concentrations in Domestic Wells and Proximity to Roadways in Vermont, *U.S. Geological Survey Open-File Report No. 2019-1148, 2020.*

Figure 2.13
Plume Movement of Contaminants Through Groundwater



Source: SEWRPC

Similarly, wastewater collection and treatment can contribute chlorides to soil which infiltrate to enter groundwater. Direct paths include discharge of effluent from WWTPs and onsite sewage treatment systems to soil and groundwater, as shown in paths "M" to "Q" and "N" to "Q," respectively, in Figure 2.4. A less direct route occurs through losses from sanitary sewers. Not all water and chloride entering a sewage collection system end up in receiving waters. Substantial amounts of exfiltration can occur from sewers. It has been estimated that about 10 to 30 percent of sanitary sewer pipes leak, providing water that can infiltrate into groundwater.[74] The amount of leakage can be substantial, on the order of 1 to 20 percent of dry-weather flow.[75] This route is also shown paths "M" to "Q" in in Figure 2.4. Many other examples of pathways of chloride from sources are shown in Figure 2.4. Clearly, chloride can reach groundwater through numerous routes.

Human activities unrelated to direct chloride applications may also lead to contamination of groundwater by chlorides. Improperly abandoned wells provide a direct pathway from the land surface to the source aquifer for the well. If runoff carries salts to such wells, it can lead to rapid contamination of the aquifer. Pumping from wells located near surface waterbodies may induce flow from surface water into groundwater. An example of this occurred in the Blackstone River in Massachusetts. Hydrogeological investigations showed that pumping from several water supply wells induced flow from the river through a highly transmissive layer of gravel connecting the well field to the river bed.[76] During low flows, an upstream wastewater treatment plant is the main source of water to the Blackstone River near these wells. The induction of flow from the river into groundwater carried chloride and other contaminants into the aquifer that the well was drawing from.

[74] *D.N. Lerner, "Identifying and Quantifying Urban Recharge—A Review,"* Hydrogeology Journal, *10:143-152, 2002.*

[75] *M. Rutsch, J. Riechermann, and P. Krebs, "Quantification of Sewer Leakage—A Review,"* Water Science and Technology, *54:134-144, 2006.*

[76] *J.A. Izbicki,* Water Resources of the Blackstone River Basin, Massachusetts, *U.S. Geological Survey Water-Resources Investigations Report No. 93-4167, 2000.*

Some low-impact-development practices may also act as sources of chloride to groundwater. Stormwater management practices such as wet retention ponds, dry detention ponds, bioswales, and rain gardens are designed to capture and infiltrate runoff from surrounding impervious surfaces. These practices serve to recharge groundwater and limit direct runoff to surface waters. A study of stormwater ponds in Owings Mill, Maryland found greatly elevated specific conductance and chloride concentrations in groundwater under the ponds, indicating the ponds were a source of chloride to groundwater.[77] The widespread use of these best management practices could potentially accelerate chloride contamination of groundwater.

Chloride Accumulation in Aquifers

When salts are applied in a stream or river basin, some of the applied chloride will be removed by flow leaving the basin. The remaining chloride will be stored in soil and groundwater. This chloride will be gradually moved to the river or stream system in baseflow and leave the basin in water flowing out. The effect on groundwater will depend on the relative magnitudes of chloride applications and losses over the course of time. If the amount of chloride being applied is greater than the amount leaving the basin through flow, chloride will accumulate in the groundwater and its concentration in the aquifer will increase. These increases will continue until the amount of chloride entering the groundwater due to applications equals the amount leaving through baseflow. At that point a steady state will be achieved with the chloride concentration and amount of chloride stored in groundwater achieving a stable level.

An example of this sort of accumulation was reported in the early 1990s for the Highland Creek basin near Toronto, Canada. Mass balance calculations showed that only about 45 percent of the chloride deposited in the basin by road deicing each year was removed by overland flow into streams and flow of water out of the basin before the next winter began.[78] In addition, most of the chloride that left the basin was flushed out during the winter in which it was applied. This suggests that as much as 55 percent of the annually applied chloride in this basin was stored in soil and groundwater. Additional calculations indicated that at the rate chloride was being applied, concentrations of chloride in groundwater of this basin would continue to increase for about 20 years before reaching a steady state.[79] At that time, the average concentration of chloride in baseflow, an indicator of groundwater concentration, would be about 426 mg/l. More recent work on the same basin indicates that about 40 percent of the annually applied chloride is stored in groundwater and that chloride concentration at steady state will be about 505 mg/l.[80]

Storage of chloride in groundwater is likely happening in many areas. This is indicated by the fact that increases in chloride concentrations in baseflow to urban streams has been reported in many locations.[81] These increases are at least partially due to chloride retention within the watershed soil and groundwater.[82]

The storage of chloride in groundwater also suggests that groundwater may act as both a sink and a source of chloride. This can result in complicated interactions with surface waterbodies. During the winter and spring, chloride concentrations in streams can be high due to the flushing of salts from impervious surfaces in their watersheds. Streams receiving groundwater discharges during winter may see mixing of higher salinity (salt content) surface water with lower salinity groundwater. In this case, the groundwater input will act to reduce chloride concentration in the stream. The opposite situation may occur during summer and

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[77] *R.E. Casey, S.M. Lev, and J.W. Snodgrass, "Stormwater Ponds as a Source of Long-Term Surface and Ground Water Salinization,"* Urban Water Journal, *10:145-153, 2013.*

[78] *K.W.F. Howard and J. Haynes, "Groundwater Contamination Due to Road-Deicing Chemicals: Salt-Balance Implication,"* Geoscience Canada, *20:1-8, 1993.*

[79] Ibid.

[80] *N. Perera, B. Gharabaghi, and K. Howard, "Groundwater Chloride Response in the Highland Creek Watershed Due to Road-Salt Application: A Re-Assessment After 20 Years,"* Journal of Hydrology, *479:159-168, 2013.*

[81] *See, for example, S. Kaushal, P.M. Groffman, G.E. Likens, K.T. Belt, W.P. Stack, L.E. Band, and G.T. Fisher, "Increased Salinization of Fresh Water in the Northeastern United States,"* Proceedings of the National Academy of Sciences, *102:13,517-13,520, 2005 and S.R. Corsi, L.A. DeCicco, M.A. Lutz, and R.M. Hirsch, "River Chloride Trends in Snow-Affected Urban Watersheds: Increasing Concentrations Outpace Urban Growth Rate and Are Common Among All Seasons,"* Science of the Total Environment, *508:488-497, 2015.*

[82] *E.V. Novotny, A.R.A. Sander, O. Mohseni, and H.G. Stefan, "Chloride Ion Transport and Mass Balance in a Metropolitan Area Using Road Salt,"* Water Resources Research, *45: W12410, 2009.*

fall months. If enough chloride is stored in groundwater, its concentration will be higher in groundwater than in the stream. Baseflow during these months will tend to increase chloride concentrations in the stream. This effect may be amplified during extended periods of drought.

Evidence of groundwater impacts was seen in Meadowbrook Creek, a stream near Syracuse, New York that is heavily impacted by road runoff. During nonwinter months, concentrations of chloride in this stream increased from upstream to downstream, implying that chloride was being contributed to the stream by groundwater through baseflow.[83] Decreasing concentrations were observed from upstream to downstream during winter months, suggesting that groundwater contributions were acting to dilute chloride in the stream. Similarly, a study of 24 watercourses in southern Ontario found that chloride concentrations were frequently higher during the warm season rather than in the cold season, indicating that winter applications of road salt can result in sustained elevated concentrations of chloride in streams throughout the year.[84]

The accumulation of chloride in groundwater and the long residence time of water in many aquifers suggests that if salt applications in a watershed are reduced, contributions of chloride in baseflow to surface waterbodies will continue for a considerable period of time, resulting in delays in ecological improvements. For example, a study of groundwater in an aquifer system in Southern Ontario that used a three-dimensional transport model projected that it would take decades to flush chlorides from groundwater in this system, even if road salt applications were completely ended.[85] This suggests that any evaluation of practices meant to reduce chloride contributions to groundwater must be conducted with the expectation that there could be a considerable time lag between the implementation of practices and improvements in groundwater chemistry.

2.5 IMPACTS OF CHLORIDE ON STREAMS AND RIVERS

Sources of Chloride to Streams and Rivers

Chloride can reach surface waters such as streams, rivers, lakes, and wetlands through several routes. These pathways are illustrated and described in Figure 2.4 and Table 2.1.

Chloride concentrations in streams and rivers from natural sources have been documented as low. Historically the mean chloride concentration of river water in North American was on the order of about 8-20 mg/l.[86] Recent average chloride concentrations in streams and rivers of southeastern Wisconsin are much higher than this. For example, the mean chloride concentration in Oak Creek during the period 2007 through 2016 was 293 mg/l.[87] Similarly, the mean chloride concentration in the Root River during the period 2005-2012 was 202 mg/l.[88] These higher than historical concentrations are not unusual for streams and rivers, especially in urban areas.[89] This indicates that much of the contribution of chlorides to surface waters comes from anthropogenic sources.

Chlorides can be deposited on surface waters from the atmosphere. This is shown in path "R" in Figure 2.4. As discussed in the previous section on sources of chlorides to soil, the amount of chloride deposited from the atmosphere is highest near the oceans and decreases with increasing distance from the sea. In southern Wisconsin, estimated annual rates of wet and dry deposition chloride are estimated to be about 0.21 to 0.51

[83] *S.H. Kincaid, L.K. Lautz and J.C. Stella, "Hydrogeologic Processes Impacting Storage, Fate, and Transport of Chloride from Road Salt in Urban Riparian Aquifers,"* Environmental Science & Technology, *50:4,979-4,988, 2016.*

[84] *A.K. Todd and M.G. Kaltenecker, "Warm Season Chloride Concentrations in Stream Habitats of Freshwater Mussel Species at Risk,* Environmental Pollution, *171:199-206, 2012.*

[85] *M.L. Bester, E.O. Frind, J.W. Molson, and D.L. Rudolph, "Numerical Investigation of Road Salt Impact on an Urban Wellfield,"* Groundwater, *44:165-175, 2006.*

[86] *J.E. Raymont,* Plankton Productivity in the Oceans, *Pergamon Press, Toronto, 1967; R.G. Wetzel,* Limnology, *Saunders College Publishing, Toronto, 1983; Hintz and Relyea 2019,* op. cit.

[87] *SEWRPC Community Assistance Planning Report No. 330,* A Restoration Plan for the Oak Creek Watershed, *December 2021.*

[88] *SEWRPC Community Assistance Planning Report No. 316,* A Restoration Plan for the Root River Watershed, *July 2014.*

[89] *See, for example, Corsi et al., 2015,* op. cit.

kg per acre[90] and 0.02 to 0.19 kg per acre,[91] respectively. While contributions of chloride to surface waters through atmospheric deposition appear to be relatively small on a regional scale, atmospheric contributions may generate impacts on a local scale.

Chloride from deicing salts can enter surface waters through several pathways. Salt applied to impervious surfaces can be carried in runoff to surface waters. This is shown in path "H" in Figure 2.4. The runoff may move directly over the land's surface or through ditches and storm sewer systems. Similarly, salt spilled during storage, processing, or transport can be carried in runoff to surface waters. This is shown in path "C" in Figure 2.4. Runoff from salt storage areas can contain high concentrations of chloride. For example, a study of a salt storage area in Massachusetts that had outdoor delivery and loading of trucks observed a monthly average chloride concentration of 13,000 mg/l in runoff from the site.[92] Chloride from deicing salts can also travel more complicated routes from impervious surfaces to surface water. As previously discussed, stormwater management practices that are designed to infiltrate runoff can serve as sources of chloride to groundwater. Discharge of groundwater as baseflow can transport chloride into nearby surface waters. This is shown as paths "J," "Q," and "V" in Figure 2.4. An example of this was observed in a study of two stormwater detention ponds in Baltimore County, Maryland.[93] Data from monitoring wells showed that chloride concentrations in groundwater were highest directly beneath the ponds. These data also showed the presence of a contamination plume extending from the ponds to a nearby stream. The authors estimated that this plume contributed about 14,500 pounds (lbs) and 88,000 lbs of chloride to the stream during the winters of 2008-2009 and 2009-2010, respectively. This study also examined chloride concentrations in streams in separate urban drainage basins within a single watershed. It found that streams in drainage basins that contained stormwater ponds have consistently higher chloride concentrations and specific conductance under baseflow conditions than those in basins without ponds. Average summer chloride concentrations in the stream were about three times higher in basins with ponds. These results suggest that the presence of infiltration practices can alter the temporal pattern of chloride delivery to streams to provide contributions throughout the year.[94]

Discharges of effluent from WWTPs can contribute substantial amounts of chloride to receiving waters. This is shown in path "L" in Figure 2.4. For example, chloride concentrations in samples collected from the effluent of the City of Oconomowoc WWTP during the period from January 2015 through April 2019 ranged between 350 mg/l and 577 mg/l, with a mean concentration of 475 mg/l. Chloride is contributed to wastewater in residential, commercial, food processing, and industrial wastes. Residential sources include human excretion, food waste, personal care products, detergents, chlorine-based cleansers, bleach, and water softening. Estimates of the amount of chloride contributed by human excretion vary by about an order of magnitude, ranging from about 3,500 mg per person per day[95] to 34,000 mg per person per day.[96] One study estimated that excretion contributed about 9,000 mg chloride per person per day, with consumer products contributing about 25,000 mg per person per day.[97]

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[90] *National Atmospheric Deposition Program 2021,* op. cit.

[91] Ibid.

[92] *D.W. Ostendorf, E.S. Hinlein, and S. Choi, "Reduced Road Salt Spillage Owing to Indoor Delivery and Loading,"* Journal of Environmental Engineering, *128:223-228, 2012.*

[93] *J.W. Snodgrass, J. Moore, S.M. Lev, and R.E. Casey, "Influence of Modern Stormwater Management Practices on Transport of Road Salt to Surface Waters,"* Environmental Science & Technology, *5:4,165-4,172, 2017.*

[94] Ibid.

[95] *J.R. Mullaney, D.L. Lorenz, and A.D. Arntson,* Chloride in Groundwater and Surface Water in Areas Underlain by the Glacial Aquifer System, Northern United States, *U.S. Geological Survey Scientific Investigations Report No. 2009-5086, 2009.*

[96] *K.S. Godwin, S.D. Hafner, and M.F. Buff, "Long-Term Trends in Sodium and Chloride in the Mohawk River, New York—The Effect of Fifty Years of Road-Salt Application,"* Environmental Pollution, *124:273-281, 2003.*

[97] *V.R. Kelly, G.M. Lovett, K.C. Weathers, S.E.G. Findlay, D.L. Strayer, D.J. Burns, and G.E. Likens, "Long-Term Sodium Chloride Retention in a Rural Watershed—Legacy Effects of Road Salt on Streamwater Concentration,"* Environmental Science & Technology, *42:410-415, 2008.*

Water softening to reduce water hardness can be a major source of chloride to wastewater treatment effluent from both WWTPs and onsite systems. Hard and very hard water can be found in aquifers consisting of rock types that are relatively soluble and contain calcium- and magnesium-bearing minerals. Examples of these types of aquifers include those found in glacial deposits, basaltic rock, sandstone, and carbonate rock.[98] With the exception of basaltic rock, aquifers of these types are commonly used as sources of water supply in southeastern Wisconsin. Most water softening conducted in residential and commercial settings is done using ion-exchange systems. These systems work by adsorbing calcium and magnesium ions, as well as iron, manganese, and other positively charged ions, on an ion-exchange resin. Adsorption of these ions on the resin displaces sodium ions. The resin is recharged by passing a sodium chloride brine through it. This produces a waste brine containing chloride ions, as well as calcium, magnesium, iron, manganese, and excess sodium ions. This waste is discharged as wastewater. The concentration and load of chloride discharged in this brine depends on several factors including the hardness of the water being treated, the amount of softening achieved, and the efficiency of the treatment system. Wastewater treatment can lead to contributions of chloride to surface water through direct discharges from WWTPs into receiving waters (path "L" on Figure 2.4) or via groundwater through discharge or loss of wastewater into soil (routes following paths "M" and "N" though paths "Q" and "V" on Figure 2.4)

The ratio of sodium to chloride (Na:Cl) in stream water can provide information suggesting the route taken by chlorides to reach the stream.[99] For instance, if road salt takes a direct path to streams through surface runoff or drainage systems the Na:Cl ratio should be similar to the mass ratio of the two elements, roughly 0.65:1. If the route includes underground transport through soil and/or groundwater, the Na:Cl ratio should be lower than this, for example 0.3:1.

As previously discussed, chloride may be stored in soil and groundwater. The fact that much of the chloride contributed to streams can pass into these environmental compartments, be stored in them, and pass back into streams has implications for the response of stream chloride concentrations to reductions in inputs of chloride to the environment. For example, following a reduction in road salting in a watershed, chloride stored in soil and groundwater may continue to enter streams, keeping stream chloride concentrations relatively high. Reductions in stream chloride concentration may be delayed until chloride has been flushed from these other compartments. This effect may occur on several different time scales. For example, chloride in salt applied to roadways during the winter can affect summertime concentrations due to storage in soil or shallow groundwater and later discharge in baseflow. Because groundwater moves much more slowly than surface water, contributions to streams in baseflow may persist for years or perhaps decades following a reduction in salt applications.

Physical and Chemical Impacts on Streams

Dissolved salts increase the density of water. In streams, this can result in the presence of a dense saline layer of water just above the sediment-water interface. Such a layer may expose benthic organisms to higher chloride concentrations than would be expected based upon sampling from the water column.[100] Density differences due to chloride and salt inputs may also lead to stratification in deeper impoundments with longer water residence times. The effects of chloride and salts on water density is more fully discussed later in this chapter in the section on the impact of chlorides on lakes.

As previously discussed, addition of chloride salts to water can lower its pH, making it more acidic. This occurs partially because addition of Na^+ and chloride (Cl^-) ions to water will mobilize H^+ ions from ion exchange sites making the water more acidic.[101] As previously mentioned, increased acidity can lead to chemical changes in water such as making metals more soluble.

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[98] *L.A. DeSimone,* Quality of Water from Domestic Wells in Principal Aquifers of the United States: 1991-2004, *U.S. Geological Survey Scientific Investigations Report No. 2008-5227, 2009.*

[99] *R.B. Jackson and E.G. Jobbágy, "From Icy Roads to Salty Streams,"* Proceedings of the National Academy of Sciences, *102:14,487-14,488, 2005.*

[100] *N. Eyles and M. Meriano, "Road-Impacted Sediment and Water in a Lake Ontario Watershed and Lagoon, City of Pickering, Ontario, Canada,"* Sedimentary Geology, i224:15-28, 2010.

[101] *S.S. Kaushal, G.E. Likens, M.L. Pace, S. Haq, K.L. Wood, J.G. Galella, C. Morel, T.R. Doody, B. Wessel, P. Kortelainen, A. Räkle, V. Skinner, R. Utz, and N. Jaworski, "Novel 'Chemical Cocktails' in Inland Waters Are a Consequence of the Freshwater Salinization Syndrome,"* Philosophical Transactions of the Royal Society, Series B, *374:20080017, 2018.*

Increases in chloride and salt concentrations in streams can lead to increases in concentrations of several substances in stream water. This includes other cations such as K^+, Ca^{2+}, and Mg^{2+} that can be mobilized from sediments in streambeds, streambanks, and suspended particles.[102] Addition of sodium chloride to riverine sediments collected across a variety of land uses resulted in consistent release of these ions.[103] This may be a factor in the long-term trend toward increasing concentrations of these cations that has been observed in many North American and European inland waters.[104]

Heavy metals may also be mobilized into stream water by additions of chloride salts. Increasing concentrations of sodium chloride led to release of Fe^{2+} ions from sediments of the Murray River in Australia.[105] Monitoring of streams and rivers in the Baltimore, Maryland and Washington, D.C. areas have also shown that sharp increases in concentrations of cadmium, copper, manganese, and zinc occur during winter months following applications of deicing salts.[106] Higher salt concentrations tended to increase the fraction of these metals that were in bioavailable forms, such as dissolved ions.[107] The mechanisms through which chloride salts mobilize heavy metals and the impacts of such mobilization were previously discussed in the section on the impacts of chloride on soil and sediment.

Increasing chloride salt concentrations can affect nutrient concentrations in streams in complex ways. Higher salt concentrations can lead to increases of dissolved forms of some nutrients in the water column as a result of their release from sediments and suspended particles. As a result, this can increase concentrations of soluble reactive phosphorus (SRP), the form of phosphorus most bioavailable to bacteria, algae, and plants; ammonium, an inorganic form of nitrogen that is readily consumed by bacteria, algae, plants; and Kjeldahl nitrogen, which consists of ammonium and organic nitrogen compounds.[108]

Increases in chloride in streamflow can also reduce rates of denitrification, the microbially-mediated process that converts nitrate to nitrogen gas, in debris jams in streams. Debris jams in streams often have a high content of organic material. Because of this, they serve as hot spots for nutrient cycling in small streams.[109] An example of a debris jam is shown in Figure 2.14. Denitrification rates are higher in debris jams than in gravel bars, pools, and riffles.[110] Laboratory studies on material removed from stream debris jams showed that increases in chloride concentration reduced the activity of the enzymes that perform denitrification and inhibited their response to increased concentrations of nitrate.[111] This effect converted the function of debris jams from removing nitrate from the stream system to providing it. This effect did not occur with material removed from debris jams in streams with a history of high chloride concentrations. This suggests that the microbial community responsible for denitrification may have the potential to adapt to higher chloride concentrations either through physiological adaptation by the microbes, development

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[102] *Hintz and Relyea 2019,* op. cit.

[103] *Haq et. al. 2018,* op. cit.

[104] *Kaushal et al. 2018,* op. cit.

[105] *D. Baldwin, G. Rees, A. Mitchell, G. Watson, and J. Williams, "The Short-Term Effects of Salinization on Anaerobic Nutrient Cycling and Microbial Community Structure in Sediment from a Freshwater Wetland,"* Wetlands, *26:455-464, 2006.*

[106] *Kaushal et al. 2018,* op. cit.

[107] *Schuler and Relyea 2018,* op. cit.*; L.A. Warren and A.P. Zimmerman, "The Influence of Temperature and NaCl on Cadmium, Copper, and Zinc Partitioning among Suspended Particles and Dissolved Phases in an Urban River,"* Water Research, *28:1,921-1,931, 1994.*

[108] *Baldwin et al. 2006,* op. cit.; *S. Duan and S.S. Kaushal, "Salinization Alters Fluxes of Bioreactive Elements from Stream Ecosystems Across Land Use,"* Biogeosciences, *12:7,331-7,347, 2015; and Haq et al. 2018,* op. cit.

[109] *H.M. Valett, C.L. Crenshaw, and P.F. Wagner, "Stream Nutrient Uptake, Forest Succession, and Biogeochemical Theory,"* Ecology, *83:2,888-2,901, 2002; M.J. Bernot and W.K. Dodds, "Nitrogen Retention, Removal, and Saturation in Lotic Ecosystems,"* Ecosystems, *8:442-453, 2005.*

[110] *P.M. Groffman, A.M. Dorsey, and P.M. Mayer, "Nitrogen Processing within Geomorphic Features in Urban Streams,"* Journal of the North American Benthological Society, *24:613-625, 2005.*

[111] *R.L. Hale and P.M. Groffman, "Chloride Effects on Nitrogen Dynamics in Forested and Suburban Stream Debris Dams,"* Journal of Environmental Quality, *35:2,425-2,432, 2006.*

of a new microbial community, or altered coupling between carbon cycle and nitrogen cycle processes.[112] Inhibition of denitrification by chloride has also been reported to occur in wetlands.[113]

Higher concentrations of chloride salts typically increase releases of dissolved organic carbon compounds (DOC) from stream bed sediments into the water column.[114] Increased salinity also altered the chemical composition of the DOC that was mobilized to the water column.[115] As salinity increased, the amount of labile DOC, compounds which are relatively easily degraded, tended to increase. Many of these labile forms consisted of proteins. This is due, in part, to the fact that solubility of proteins tends to increase with increases in a solution's ionic strength.[116] Conversely, increases in salinity tend to reduce the amount of DOC consisting of aromatic compounds, which are more resistant to degradation. This reflects that fact that increasing ionic strength tends to reduce the solubility of nonpolar or weakly polar organic compounds in water.[117]

Figure 2.14
Debris Jam with Accumulated Organic Matter

Source: SEWRPC

The effects of higher concentrations of salts on the release of DOC to the water column tended to increase with the degree of urbanization in the watershed.[118] This may reflect changes in the organic matter content of stream sediments that accompany urbanization. Urban stream sediments tend to contain greater amounts of organic matter than those in rural areas. This may be due to organic matter contributions from algal and wastewater sources that are associated with urban areas. It has also been found that gross primary production, which measures production of organic matter, and the lability of stream organic matter to degradation increase with increasing watershed urbanization.[119]

Increases in DOC affect other processes in streams. Higher amounts of DOC tend to reduce the transparency of water. This reduces light penetration and can affect the amount of photosynthesis occurring within the stream. Lower photosynthesis can have impacts on the composition of and production by biological communities. Increases in DOC can also alter acidity and metal transport in streams. There is widespread evidence that DOC has increased in freshwaters in both North America and Europe since about 1990.[120] Increasing concentrations of chloride salts may be one factor promoting this increase in DOC.

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[112] Ibid.

[113] *N.A. Lancaster, J.T. Bushey, C.R. Tobias, B. Song, and T.M. Vadas, "Impact of Chloride on Denitrification Potential in Roadside Wetlands,"* Environmental Pollution, *212:216-223, 2016.*

[114] *Duan and Kaushal 2015,* op. cit.

[115] Ibid.

[116] *Amrhein et. al. 1992,* op. cit.

[117] *B.K. Brunk, G.H. Jirka, and L.W. Lion, "Effects of Salinity Changes and the Formation of Dissolved Organic Matter Coatings on the Sorption of Phenanthrene: Implications for Pollutant Trapping in Estuaries,"* Environmental Science and Technology, *31:119-125, 1997.*

[118] *Duan and Kaushal 2015,* op. cit.

[119] *S.S. Kaushal, K. Delaney-Newcomb, S.E.G. Findlay, T.A. Newcomer, S. Duan, M.J. Pennino, G.M. Sivirichi, A.M. Sides-Raley, M.R. Walbridge, and K.T. Belt, "Longitudinal Patterns in Carbon and Nitrogen Fluxes and Stream Metabolism Along an Urban Watershed Continuum,"* Biogeochemistry, *121:23-44, 2014.*

[120] *C.T. Driscoll, K.M. Driscoll, K.M. Roy, and M.J. Mitchell, "Chemical Response of Lakes in the Adirondack Region of New York to Declines in Acidic Deposition,"* Environmental Science and Technology, *27:2,036-2,042, 2003; J. Hejzlar, M. Dubrovsky, J. Buchtele, and M. Ruzicka, "The Apparent and Potential Effects of Climate Change on the Inferred Concentration of Dissolved Organic Matter in a Temperate Stream (the Male River, South Bohemia),"* Science of the Total Environment, *310:142-152, 2003; C. Evans, D.T. Monteith, and D.M. Cooper, "Long-Term Increases in Surface Water Dissolved Organic Carbon: Observations, Possible Causes and Environmental Impacts,"* Environmental Pollution, *137:55-71, 2005.*

2.6 IMPACTS OF CHLORIDES ON LAKES

Sources of Chloride to Lakes

The sources of chloride to lakes are similar to those that were previously discussed for streams and rivers. Chlorides can be contributed to lakes by the atmosphere through wet and dry deposition. Chloride from deicing salts can enter lakes in runoff carried from imperious surfaces either through overland flow, ditches and storm sewers, or groundwater (path "H" and paths "B" to "Q" to "V" on Figure 2.4). Chlorides from water softening can be carried into lakes through streamflow from WWTPs discharging upstream and through groundwater from onsite systems and WWTPs (path "L" and paths "N" to "Q" to "V" and "M" to "Q" to "V" on Figure 2.4). Streamflow into lakes with inlets will contribute chloride to lakes. The pathways of chloride into surface waters are discussed more fully in the section above on sources of chloride to streams and rivers.

Lake residence time is an important factor influencing the concentration of chloride in a lake, especially lakes that have one or more inlets and an outlet. Residence time is the average amount of time that water or a dissolved substance spends in a lake before being flushed out. It is determined by the volume of the lake and the rate of water flow through the lake. Reported residence times for several lakes in southeastern Wisconsin are shown in Table 2.2. Residence times range from days, such as for the Waterford Impoundment, to several years such as for Fowler Lake. Residence time varies with weather conditions, so the times shown in the table should be interpreted as relative orders of magnitude.

Longer residence times allow chloride to build up in lakes, increasing concentrations. Because of rapid flushing, chloride may not build up in lakes with shorter residence times; however, these lakes may be more sensitive to rapid changes in chloride inputs. They may also be more sensitive to the influence of chloride in groundwater.

Ice formation can increase the concentration of chloride in the water column through the process of ion exclusion. When water freezes, dissolved ions such as chloride are not incorporated into the ice crystal structure. Instead, they are rejected into the surrounding water.[121] The rate of exclusion of ions during ice formation in lakes have been estimated as ranging between about 60 and 99 percent based on concentrations of chloride[122] or ions[123] or levels of specific conductance.[124] A study of the Class of 1981 Marsh, a shallow wetland with open water on the University of Wisconsin campus in Madison, found that ice formation increased the concentration of chloride in the water from about 240 mg/l to 1,250 mg/l.[125] The maximum concentration of chloride coincided with the maximum thickness of ice cover. In addition, changes in chloride concentration were correlated with changes in the thickness of ice cover. Ion exclusion is likely to be a small to negligible factor influencing chloride concentrations in the water column of deep lakes because ice cover represents a small portion of the volume of water in the lake. Shallow lakes and wetlands are likely to be more sensitive to seasonal increases in chloride as a result of ion exclusion during ice formation.

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[121] *D. Notz and M.G. Worster, "Desalination Processes of Sea Ice Revisited,"* Journal of Geophysical Research, *114: C05006, doi: 10.1029/2008JC004885, 2009.*

[122] *H.A. Dugan, G. Helmueller, and J.J. Magnuson, "Ice Formation and the Risk of Chloride Toxicity in Shallow Wetlands and Lakes,"* Limnology and Oceanography Letters, *2:150-158, 2017.*

[123] *C. Belzile, J.A.E. Gibson, and W.F. Vincent, "Colored Dissolved Organic Matter and Dissolved Organic Carbon Exclusion from Lake Ice: Implications for Irradiance Transmission and Carbon Cycling,"* Limnology and Oceanography, *47:1,283-1,293, 2002.*

[124] *R. Pieters, and G.A. Lawrence, "Effect of Salt Exclusion from Lake Ice on Seasonal Circulation,"* Limnology and Oceanography, *54:401-412, 2009; She, Y., J. Kemp, L. Richards, and M. Loewen, "Investigation into Freezing Point Depression in Stormwater Ponds Caused by Road Salt,"* Cold Regions Science and Technology, *131:53-64, 2016; C.E. Bluteau, R. Pieters, and G.A. Lawrence, "The Effects of Salt Exclusion During Ice Formation on Circulation in Lakes,"* Environmental Fluid Mechanics, *17:579-590, 2017.*

[125] *Dugan et al. 2017,* op. cit.

Table 2.2
Reported Water Residence Times for Lakes in Southeastern Wisconsin

Lake	Residence Time (years)	Lake	Residence Time (years)
Ashippun Lake	2.30	Oconomowoc Lake	0.45
Bark Lake	0.37	Okauchee Lake	0.90
Beaver Lake	2.60	Pewaukee Lake	2.30
Benedict Lake	5.50	Pike Lake	1.10
Cravath Lake	0.25	Pin Lake	5.20
Crooked Lake	0.01	Pleasant Lake	0.30
Delavan Lake	2.00	Powers Lake	3.80
Denoon Lake	3.60	Pretty Lake	3.30
Eagle Spring Lake	0.07	Rice Lake	7.07
Elizabeth Lake	1.85	Rock Lake	1.80
Fowler Lake	6.90	School Section Lake	0.14
Friess Lake	0.30	Silver Lake (Washington County)[a]	3.20
Geneva Lake[a]	13.90	Tombeau Lake	0.20
George Lake	0.18	Trippe Lake	1.75
Keesus Lake	2.00	Upper Nemahbin Lake	0.55
Lake Mary	1.92	Upper Phantom Lake	0.99
Lake Michigan	99.00	Voltz Lake[a]	2.20
Little Muskego Lake[a]	0.90	Wandawga Lake	2.00
Lower Phantom Lake	0.04	Waterford Impoundment	0.03
Lulu Lake	0.09	Whitewater	1.02
Nagawicka Lake	0.80	Wind Lake	0.60
North Lake	0.80		

[a] *As part of the regional chloride study, Commission staff conducted monitoring on these lakes. In addition, Commission staff monitored two lakes for which water residence times were not available: Big Cedar Lake and Moose Lake.*

Source: SEWRPC

Inhibition of Mixing

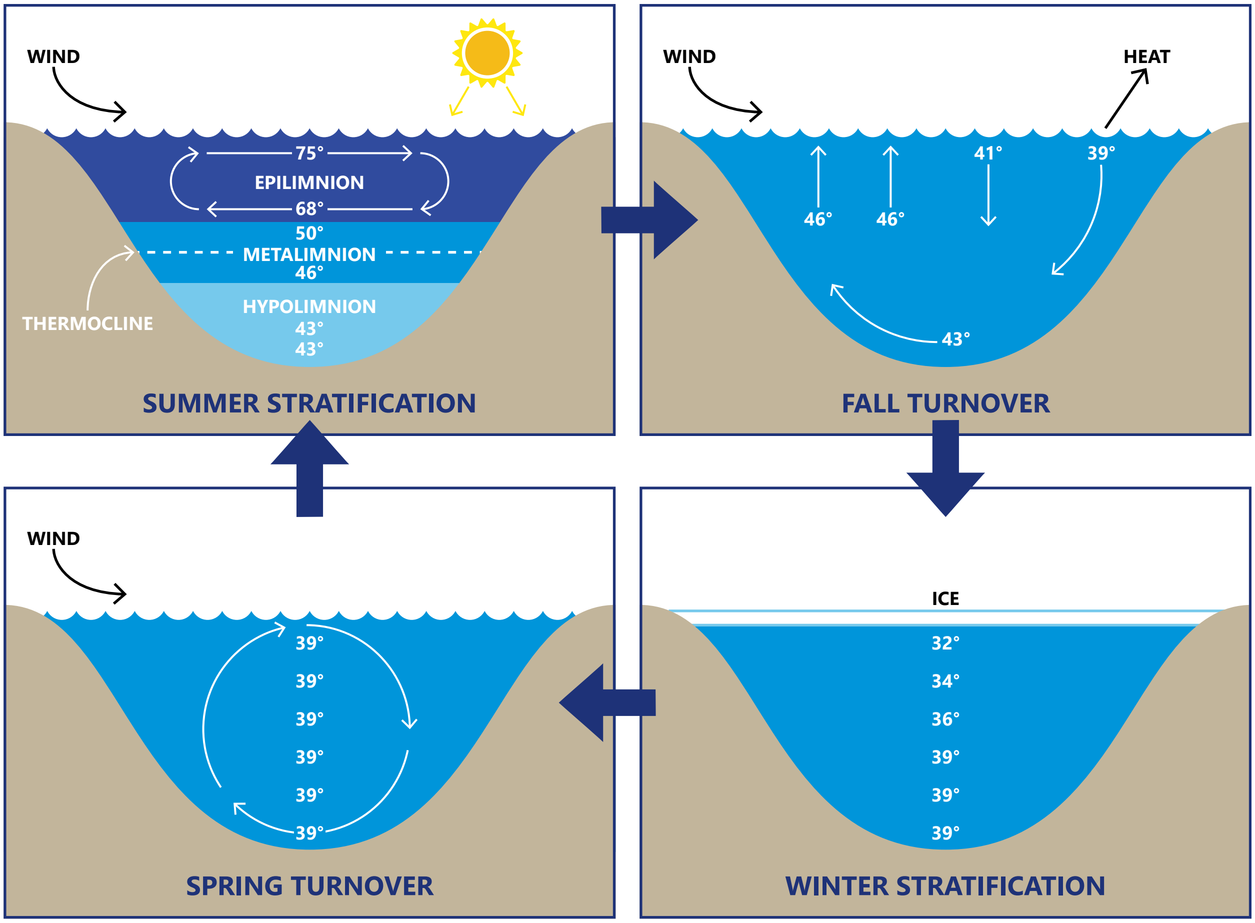
Seasonal Mixing and Stratification of Lakes

Stratification in a lake occurs when there are density differences between layers of water that cause water near the lake surface (epilimnion) to float on deeper water (hypolimnion). This is commonly caused by temperature differences between surface water and deeper waters. The maximum density of water occurs at about 39°F. As the water temperature increases or decreases from 39°F its density decreases.

A lake must be relatively deep to generate sufficient temperature differences between surface and bottom waters for the lake to stratify. In general, lakes in southeastern Wisconsin less than 15 feet deep are unlikely to stratify, whereas lakes with depths greater than 20 feet are likely to stratify. The propensity of a lake to stratify is heavily influenced by its shape, size, orientation, landscape position, surrounding vegetation, through flow, water sources, the prevailing direction and strength of wind, and a host of other factors. Depth to the thermocline, the transitional layer between the epilimnion and hypolimnion, can range from less than 10 feet to 30 feet in typical Southeastern Wisconsin lakes. Even within the same lake, the depth and thickness of the thermocline may differ from season to season and year to year. Water within the thermocline rapidly cools with depth and often contains less oxygen than the epilimnion. Below the thermocline, water in the hypolimnion is much colder than water at the lake surface and may not mix with the epilimnion until fall. Little sunlight penetrates past the thermocline; therefore, deeper portions of lakes generally do not support significant photosynthetic activity and hence do not receive oxygen from plants.

Most deep lakes in the Region stratify sometime during mid to late spring, with a short period, usually less than a week, of whole-lake water circulation and mixing (turnover) that takes place once during spring and once again in fall. This pattern is shown in Figure 2.15. Following ice out in the spring, the density differences in the water column are typically small enough to allow the wind to mix the lake. During the fall as air temperatures cool, water in the epilimnion cools. Eventually this water becomes denser than the warmer water below and sinks. Along with wind action, this mixes the lake. At turnover, the lake water temperature and chemistry are uniform from the lake surface to the lake bottom.

Figure 2.15
Typical Seasonal Thermal Stratification Within Deeper Lakes



Note: Temperatures are in degrees Fahrenheit.

Source: Modified from B. Shaw, C. Mechenich, and L. Klessig, Understanding Lake Data, *University of Wisconsin-Extension, p. 3, 2004 and SEWRPC*

Lakes that mix twice per year are termed dimictic lakes. Most Wisconsin lakes that are deep enough to stratify are dimictic. Some lakes may only mix once during the year. They are referred to as monomictic lakes. Under certain conditions, some lakes remain permanently stratified. They are referred to as meromictic lakes.

While stratification is generally associated with temperature, chemical conditions in a lake can alter its density structure and affect stratification and mixing. Contributions of chloride to a lake can increase the density of hypolimnetic water. Since water containing chloride salts is denser than uncontaminated water, salt-contaminated runoff that enters a lake will sink to the bottom and create a density gradient between the bottom and the surface waters. This gradient can inhibit seasonal mixing and turnover. This inhibition can include delaying turnover, reducing the depth to which the lake mixes during turnover, preventing turnover during either spring or fall of some years, or permanently preventing turnover from occurring.

Density gradients due to salt inputs and inhibition of mixing and turnover have been detected in several lakes. Some examples are described in the following sections.

Examples of Lakes with Mixing Inhibited by Chloride Contributions

Third Sister Lake, Michigan

Third Sister Lake is a small kettle lake near Ann Arbor, Michigan. This lake has a surface area of about 9.5 acres, maximum depth of about 57 feet, and a watershed area of about 272 acres. Historical studies showed that the lake regularly turned over during the spring and fall and regularly mixed completely during turnover during the 1940s.[126] Over the period 1981 through 1989, the average concentration of chloride in this lake increased from 19 mg/l to 260 mg/l.[127] The period of rapid increase corresponded to the construction of office parks, an industrial park, and associated parking lots in the watershed to the lake.[128] Runoff from these areas is conveyed to the lake through influent streams. By March 1989, a gradient of chloride with depth was present in Third Sister Lake following ice out, with concentrations ranging from 230 mg/l at the surface to 293 mg/l near the bottom and complete mixing occurred only infrequently.[129] The study showed that whole lake stability, a measure of how much wind energy is needed to completely mix the lake at spring turnover, had increased by 63 percent between 1981 and 1999. In 2003, spring lake mixing was inhibited. Stratification set up immediately following ice out and thermal mixing occurred only to a depth of 20 feet.[130] In 2003 chloride concentrations in the lake ranged from 287 mg/l at the surface to 409 mg/l near the bottom, with an average concentration of 326 mg/l.

Woods Lake, Michigan

Woods Lake is a small kettle lake in the City of Kalamazoo, Michigan. This lake has a surface area of about 24 acres, maximum depth of about 46 feet, and a watershed area of about 200 acres. About 84 percent of the land use in the watershed consists of urban development, mostly residential development with some commercial development. The lake has no natural inflow or outflow; however, five stormwater outfalls discharge into it. The lake transitioned to meromixis, a state of permanent stratification, due to sustained inputs of road salt.[131] Chloride concentrations in bottom water reached about 290 mg/l. The difference in density between the lake surface water and bottom water was equivalent to that which would result from a temperature difference of about 29°F. Subsequent work showed the presence of a strong gradient of specific conductance, a surrogate for chloride concentrations, with lake surface waters showing specific conductance of about 500 microSiemens per centimeter (μS/cm) and bottom waters showing specific conductance of about 1,000 μS/cm.[132]

Mirror Lake, New York

Mirror Lake is a small lake in the Village of Lake Placid, New York. This lake has a surface area of about 124 acres, maximum depth of about 59 feet, and a watershed area of about 301 acres. About 27 percent of the land use in the watershed consists of urban development; however, much of this development is concentrated directly around the lake, including a system of roads which surround the lake. About 9 percent of the watershed consists of impervious surface which may be treated with road salt, including roads, parking lots, driveways, and sidewalks. The lake has a natural inlet and outlet. In addition, 22 stormwater outfalls discharge into the lake. Sampling from these outfalls during winter showed chloride concentrations in discharge entering the lake ranging between 500 mg/l and 2,500 mg/l.[133] The lake showed different mixing behavior in the springs of 2016 and 2017.[134] While complete mixing occurred in spring 2016, in

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[126] *F.E. Eggleton, "A Limnological Study of the Profundal Bottom of Certain Fresh-Water Lakes,"* Ecological Monographs, *1: 231-332, 1931; J.T. Lehman and T. Naumoski, "Net Community Production and Hypolimnetic Nutrient Regeneration in a Michigan Lake,"* Limnology and Oceanography, *31:788-797, 1986.*

[127] *T.B. Bridgeman, C.D. Wallace, G.S. Carter, R. Carvajal, L.C. Schiesari, S. Aslam, E. Cloyd, D. Elder, A. Field, K.L. Schulz, P.M. Yurista, and G.W. Kling, "A Limnological Survey of Third Sister Lake, Michigan with Historical Comparisons,"* Journal of Lake and Reservoir Management, *16:253-267, 2000.*

[128] *K.E. Judd, H.E. Adams, N.S. Bosch, J.M. Kostrzewski, C.E. Scott, B.M. Schultz, D.H. Wang, and G.W. Kling, "A Case History: Effects of Mixing Regime on Nutrient Dynamics and Community Structure in Third Sister Lake During Late Winter and Early Spring 2003,"* Lake and Reservoir Management, *21:316-329, 2005.*

[129] *Bridgeman et al. 2000,* op. cit.

[130] *Judd et al. 2005,* op. cit.

[131] *R.J. Siebert, C.M. Koretsky, and D.A. Wyman, "Cultural Meromixis: Effects of Road Salt on the Chemical Stratification of an Urban Kettle Lake,"* Chemical Geology*, 395:126-137, 2011.*

[132] *D. Dupuis,* The Influence of Road Salt on Seasonal Mixing and Redox Stratification in Three Southwest Michigan Kettle Lakes, *Master's Thesis, Western Michigan University, Kalamazoo, Michigan, December 2017.*

[133] *B.W. Wiltse, C.L. Laxon, N.C. Pionteck, and E.C. Yerger,* Mirror Lake 2016 Water Quality Report, *Ausable River Association, Wilmington, New York, 2017.*

[134] *B.L. Wiltse, E.C. Yerger, and C.L. Laxon, "A Reduction in Spring Mixing Due to Road Salt Runoff Entering Mirror Lake (Lake Placid, New York),"* Lake and Reservoir Management, *36:109-121, 2019.*

2017 stratification set up immediately following ice out. During the winter of 2016-2017, a strong density gradient developed under the ice. The timing and increase in the strength of this gradient corresponded to inputs of chloride into the lake. During spring 2017, a strong chloride gradient was associated with depth, ranging from 19 mg/l in surface water to 123 mg/l in bottom waters. The effect of chloride gradient on water density is the equivalent of a 5°F difference in temperature. This effect on density would be in addition to that caused by the temperature difference between surface and bottom waters. The lack of mixing in spring 2017 resulted in a longer duration and greater spatial extent of anoxic conditions in lake bottom waters. It is likely that the lake mixed in spring 2016 due to lower inputs of road salt. The winter of 2015-2016 was relatively mild and had lower than average snowfall. This led to about a 30-40 percent reduction in road salt applications. In addition, several rain events occurred during this winter[135] which may have diluted stormwater chloride concentrations.

Lakes in the Twin Cities Metropolitan Area

A study examined the response of 13 lakes in the Minneapolis-St. Paul metropolitan area to applications of road salt in 2004 through 2007.[136] The surface area of these lakes ranged from 124 acres to 884 acres. Maximum lake depths were between 25 feet and 57 feet. The lakes had watershed areas between 190 acres and 10,820 acres, with the amount of impervious surface in the watersheds ranging from 21 percent to 39 percent. Each lake received runoff from a major highway or road. During the winter, gradients in chloride concentration from the surface to the bottom formed in each of the lakes. The time of formation of this chemical stratification coincided with peak salt concentrations in streams in the Twin Cities metropolitan area. Five lakes showed much stronger chemical stratification than the others. These lakes all had the smallest surface-area-to-depth ratios of the lakes studied. Two of these lakes showed monomictic behavior, with mixing occurring once during the year and no turnover occurring during the spring. The study also found that the occurrence of spring mixing was delayed in some other lakes.

Irondequoit Bay, Lake Ontario, New York

Irondequoit Bay is a coastal bay on the southern shore of Lake Ontario near Rochester, New York. The bay is a finger-like projection into the land with a maximum length of about 4.1 miles and a maximum width of about 0.75 miles. The bay has a surface area of 1,664 acres, a maximum depth of 78 feet, and a mean depth of 22 feet. The northern end of the bay is separated from Lake Ontario by a 1.25-mile long, 490-foot-wide sandbar. The bay has a watershed area of about 169 square miles that contains urban, suburban, and rural land uses. The watershed is intersected by highways and roads that were heavily treated with deicing salts in the late 1960s and early 1970s. Most runoff entering the bay comes through Irondequoit Creek, but some enters through several smaller streams.

Historical studies showed that the bay mixed completely to the bottom in spring 1940.[137] Application of deicing salts in the watershed increased throughout the 1950s and 1960s, reaching a maximum of over 84,400 tons in winter 1969-1970.[138] Studies conducted in the early 1970s showed several impacts from applications of deicing salts in the watershed.[139] Concentrations of chloride during the summer in Irondequoit Creek and in surface waters of Irondequoit Bay had quadrupled between the 1950s and early 1970s. Concentrations

[135] *J.W. Sutherland, S.A. Norton, J.W. Short, and C. Navitsky, "Modeling Salinization and Recovery of Road-Salt Impacted Lakes in Temperate Regions Based on Long-Term Monitoring of Lake George, New York (USA) and Its Drainage Basin,"* Science of the Total Environment, *637-638:282-294, 2018*.

[136] *E.V. Novotny, D. Murphy, and H.G. Stefan, "Increase of Urban Lake Salinity by Road Deicing Salt,"* Science of the Total Environment, *406:131-144, 2008*.

[137] *W.L. Tressler, T.S. Austin, and E. Orban, "Seasonal Variation of Some Limnological Factors in Irondequoit Bay, New York,"* American Midland Naturalist, *49:878-903, 1953*.

[138] *R.C. Bubeck and R.S. Burton,* Changes in Chloride Concentrations, Mixing Patterns, and Stratification Characteristics of Irondequoit Bay, Monroe County, New York after Decreased Use of Road-Deicing Salts, 1974-1984, *U.S. Geological Survey Water-Resources Investigation Report No. 87-4223, 1989*.

[139] *R.C. Bubeck, W.H. Diment, B.L. Deck, A.L. Baldwin, and S.D. Lipton, "Runoff of Deicing Salt Effect on Irondequoit Bay,"* Science, *172:1,128-1,132, 1971; R.C. Bubeck,* Some Factors Influencing the Physical and Chemical Limnology of Irodequoit Bay, Rochester, New York, *Ph.D. Dissertation, University of Rochester, Rochester, New York, 1972; W.H. Diment, R.C. Bubeck, and B.L. Deck, "Some Effects of Deicing Salts on Irondequoit Bay and Its Drainage Basin,* Highway Research Record, *425:23-35, 1973*.

of chloride in Irondequoit Creek during the winter reached 600 mg/l by the early 1970s. Runoff containing high chloride concentrations accumulated in bottom waters of the bay. This caused a density gradient that prevented complete mixing during spring in the years 1970 through 1973. As chloride accumulated in the bay, the onset of fall turnover was delayed and required colder water temperatures. In 1939, fall turnover occurred in mid-October at a water temperature of about 54°F.[140] By the falls of 1971 and 1972, fall turnover was occurring in early to mid-December at water temperatures of about 39°F.[141] This lengthened the period of summer stratification and anoxia in bottom waters of the bay.

During the mid-1970s Monroe County, New York, where Irondequoit Bay's watershed is located, and the municipalities in the County implemented a program to reduce the use of deicing salts.[142] By winter 1974-1975, the amount of salt applied decreased to 46 percent of the peak 1969-1970 level. By winter 1979-1980, the salt amount applied represented about 30 percent of peak levels. As a result of the decrease in deicer applications, the bay mixed completely in spring 1975 and subsequent springs through 1983. Fall mixing also began earlier in the year. In the falls of 1975 and 1976, turnover occurred three to four weeks earlier and at water temperatures about 7°F warmer than in 1971 and 1972.

Irondequoit Bay failed to completely mix during spring 1984. While salt applications in its watershed had increased to about 49 percent of the peak 1969-1970 level during winter 1983-1984, the failure to mix was attributed to a larger than normal amount of salt entering the bay due to storms in late winter.[143]

Effects of Prolonged Stratification

When a lake is stratified, shallow water is considerably warmer and is well oxygenated, and is the portion of the lake supporting the greatest abundance and diversity of aquatic life. Stratification impedes vertical water circulation which in turn limits transfer of oxygen, other dissolved gases, and chemicals between near-surface water and deep-water areas (see Figure 2.15). In a stratified lake, deeper hypolimnetic water cannot exchange gases with the atmosphere. Metabolic processes continue to consume oxygen in the hypolimnion. If oxygen demands are high, such as in a nutrient enriched lake, or if the volume of deep isolated hypolimnetic water is small, limiting oxygen storage potential, oxygen concentrations in deep areas of the lake can become extremely low (hypoxic) or fall to zero (anoxic). Oxygen will be restored to the hypolimnion only during turnover. Because of this, anything that can affect lake mixing can affect the amount of lake volume that is available as habitat to aquatic organisms. Lengthening the duration of summer stratification will reduce the volume of the lake that is available as habitat.

Anoxic conditions can cause major changes in the chemistry of hypolimnetic water. These changes can occur through at least two processes. First, if sufficient organic material is present in the hypolimnion or sediment, bacteria will switch from using aerobic respiration which requires oxygen to anaerobic respiration which requires other materials as a substitute for oxygen. Examples of these other materials include converting nitrate to nitrogen gas, manganese (IV) ions to manganese (II) ions, iron (III) ions to iron (II) ions, sulfate to sulfide, and organic carbon compounds to methane. In the case of manganese and iron, these anoxic conversions make the material more soluble in water. Second, the lack of oxygen and the materials released through anaerobic respiration can alter oxidation-reduction conditions in the water. This can affect many different chemical processes, including altering the solubility of substances in the sediment. This alteration often can make some substances more soluble in water. This can result in the release of metals, including heavy metals, and phosphorus from the sediment into the hypolimnion. With both these processes, the materials resulting from anoxia can build up in the hypolimnion and can be released to water throughout the lake or to the atmosphere during turnover. This can lead to the release of methane or hydrogen sulfide gas to the atmosphere. The potential impacts of heavy metal release were previously discussed in the section on the impacts of chloride on soil and sediment.

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[140] *Tressler et al. 1953,* op. cit.

[141] *Bubeck and Burton 1989,* op. cit.

[142] Ibid.

[143] Ibid.

Figure 2.16 illustrates the chemical changes that can be caused by anoxic conditions during stratification. The figure shows a set of water samples collected for the Chloride Impact Study at different depths from Voltz Lake, a 61-acre lake in Kenosha County, Wisconsin that has a maximum depth of 24 feet and an average depth of seven feet. The samples were collected in August 2019 when the lake was strongly stratified. The samples are arranged as a series by depth. The sample on the far right was collected near the surface. From right to left, the samples were collected from progressively deeper water. The two samples on the right were collected from the epilimnion, at three- and 10-foot depths, respectively. The water in these samples is clear. The two samples on the left were collected from the hypolimnion, at 20- and 24-foot depths, respectively. They show distinct coloration, with the deeper sample having a darker color. This color likely came from dissolved materials released from the sediment under anoxic conditions. The middle sample was collected near the bottom of the thermocline at a depth of 15 feet. It has slight coloration, indicating that some of the substances released from the sediment are beginning to diffuse into the thermocline.

Factors That Affect Chloride Impacts on Lake Mixing

Several factors can influence the propensity of a lake to mix and the strength of mixing that occurs. These factors include lake size, depth, and surrounding topography which influence the sensitivity of a lake to chloride impacts to mixing.

The size of a lake is particularly important for mixing. Small, deep lakes and deep lakes with relatively small surface areas are at greater risk for disruption of mixing by chloride than larger lakes. This sensitivity comes from at least two characteristics of smaller lakes. First, they contain less water and are less able to dilute inputs of salts.[144] Second the relatively small surface area of a smaller lake provides less opportunity for energy to be transferred from wind to the water at the lake surface. This reduces the energy available to drive mixing.

The morphometry of a lake basin and the characteristics of its surrounding area can influence its propensity to mix. Lake Mary, a small meromictic lake in Vilas County, Wisconsin provides an extreme example of the effects of these factors.[145] Lake Mary has a surface area of about three acres and a maximum depth of 71 feet. The lake basin is almost circular, with a length of 410 feet and width of 394 feet. The bathymetry of the lake shows that it is roughly cone shaped. It is surrounded by heavily forested hills that shelter it from the wind. While Lake Mary is permanently meromictic, the density difference between the upper and lower water layers is very small, much smaller than is usually seen in meromictic lakes. Meromixis in this lake would probably not be sustained if density was the only factor causing it. A study of this lake concluded that the morphometry of its basin and the sheltered characteristics of the surrounding area were the dominant factors maintaining meromixis.[146] While this is an extreme example, it highlights the influence that the surrounding area and the three-dimensional shape of a lake basin have on mixing. The small density differences between water layers suggests that strong winds should be able to generate turnover in the fall as temperatures drop; however, the sheltered location of the basin ensures that the lake surface rarely, if ever, experiences strong winds. Similarly, the cone shape of the basin provides physical resistance to mixing. A more elongated lake of similar volume with its long side oriented in the direction of prevailing winds would require less wind energy to initiate mixing.

The example of Lake Mary illustrates factors that can make a lake sensitive to chloride inputs causing inhibition of mixing. As previously stated, small, deep lakes are particularly sensitive to disruption of mixing by chloride. Similarly, elongated lakes that have a major axis that is oriented perpendicular to the direction of prevailing winds may be at greater risk than those with a major axis oriented parallel to the direction of prevailing winds. Lakes located in areas that are sheltered from winds are also likely to be at greater risk for disruption of seasonal mixing.

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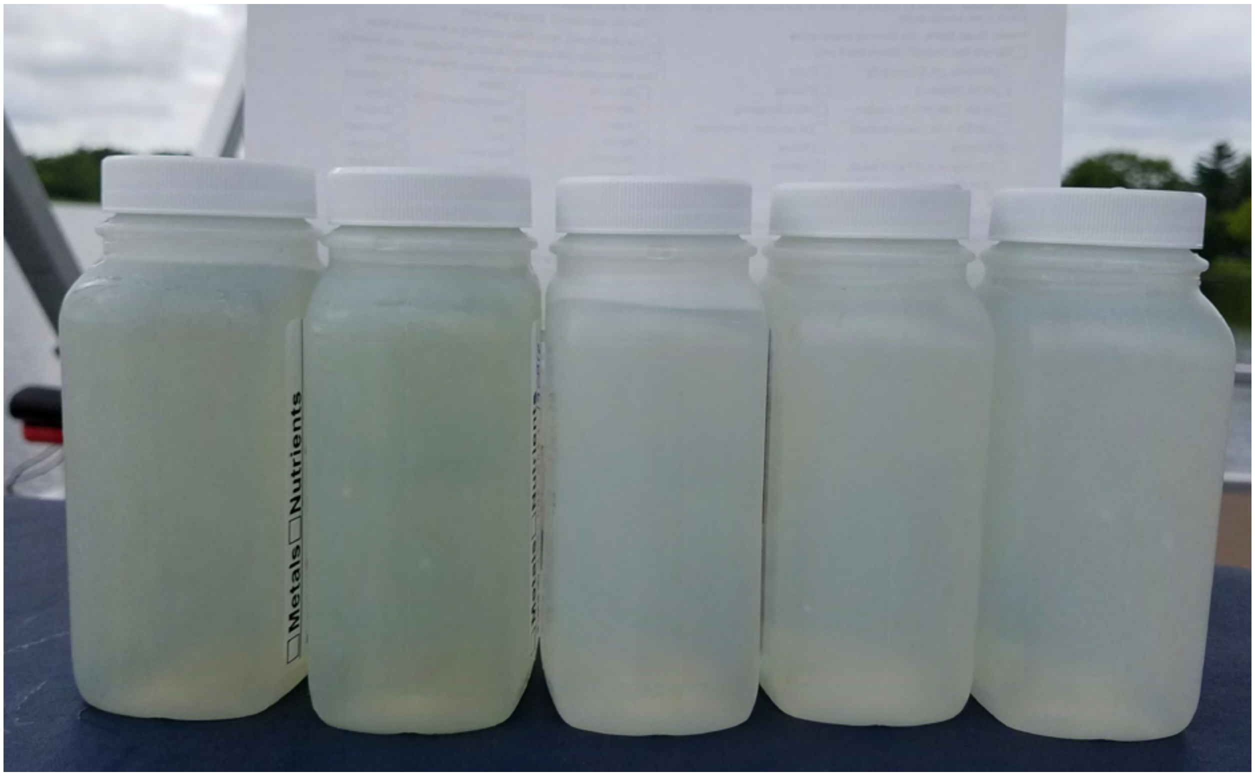
[144] *P.H. Jones and B.A. Jeffery, "Environmental Impact of Road Salting," pages 1-97 in F.M D'Itri (editor),* Chemical Deicers and the Environment, *Lewis Publishing, 1992.*

[145] *W.C. Weimer and G.F. Lee, "Some Considerations of the Chemical Limnology of Meromictic Lake Mary,"* Limnology and Oceanography, *18:414-425, 1973.*

[146] Ibid.

Figure 2.16
Water Samples from Different Depths in Voltz Lake, Kenosha County, Wisconsin – August 14, 2019



Source: SEWRPC

2.7 IMPACTS OF CHLORIDE ON WETLANDS

Sources of Chlorides to Wetlands

Natural concentrations of chloride in inland, freshwater wetlands are low, on the order of 0 to 12 mg/l.[147] Wetlands impacted by chloride may have much higher concentrations than these. A recent review reported that concentrations in chloride-contaminated wetlands ranged between 10 and 13,500 mg/l.[148]

Chlorides can be contributed to wetlands by the atmosphere through wet and dry deposition (path “R” on Figure 2.4). Chloride from deicing salts can enter wetlands in runoff carried from impervious surfaces either through overland flow or ditches and storm sewers through path “H”. Chloride from deicing salts can also enter wetlands through groundwater contributions through paths “B” to “Q” to “V” on Figure 2.4). Chlorides from water softening can be carried into wetlands through streamflow from WWTPs discharging upstream into streams and through groundwater from onsite systems (path “L” and paths “N” to “Q” to “V” on Figure 2.4). Streamflow into wetlands will also contribute chloride. The pathways of chloride into surface waters such as wetlands are discussed more fully in the section above on sources of chloride to streams and rivers.

Effects of Chloride and Salinization on Wetland Processes

Freshwater wetlands are hotspots for biogeochemical transformations.[149] These transformations are important in the cycling of plant nutrients such as phosphorus, nitrogen, sulfur, and iron. They are also important in cycling of carbon and influence sequestration of carbon and release of greenhouse gases.

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[147] *Hintz and Relyea 2019,* op. cit.

[148] Ibid.

[149] *E.R. Herbert, P. Boon, A.J. Burgin, S.C. Neubauer, R.B. Franklin, M. Ardón, K.N. Hopfensperger, L.P.M. Lamers, and P. Gell, “A Global Perspective on Wetland Salinization: Ecological Consequences of a Growing Threat to Freshwater Wetlands,”* Ecosphere, *16:Article 206, 2015.*

Contamination of wetlands by chloride and other salts can affect these transformation processes, impacting the ecosystem services provided by wetlands.

Inputs of chloride salts into wetlands can lead to the release of heavy metals that are sequestered in wetland soils and sediments. The mechanisms through which this can occur include disruption of soil structure, changes in the chemical environment including changes in pH and oxidation-reduction potential, and cation exchange. These mechanisms were previously discussed in the section on impacts of chloride and chloride salts on soil and sediment. Release of heavy metals can be a particular problem in wetlands because heavy metals can accumulate due to the high organic content of wetland soils and sediments and the tendency for these metals to bind to organic matter.

Elevated concentrations of ions like chloride reduce the solubility of gases in water.[150] Lower solubility can reduce the depth to which oxygen penetrates wetland soils, altering the oxidation-reduction potential within the soil. This can reduce the amount of time that the gases spend in the soil, reducing the time available for internal processing of gases such as oxidation of methane or reduction of nitrous oxide (N_2O), potentially accelerating emissions of such gases.[151] An additional factor that may increase gas emission is that higher ionic strength can cause hydrophobic soil colloids to repel one another which can lower hydraulic conductivity and slow the transport of gases through waterlogged wetland soils.[152]

Effects on Nitrogen Cycling

Figure 2.17 shows a simplified version of the nitrogen cycle. Nitrogen fixing bacteria, such as cyanobacteria, convert nitrogen gas into ammonium. Because oxygen interferes with the enzyme responsible for the reaction, this occurs under anaerobic conditions or in specialized bacterial cells that exclude oxygen. Bacteria can convert the ammonium to nitrite and then nitrate through the process of nitrification. The reactions that do this require oxygen. Ammonium, nitrite, and nitrate can be taken up by plants and used for growth. Other bacteria will convert nitrite back to nitrogen gas through the process of denitrification. This may occur directly or through intermediates of nitric oxide (NO) or nitrous oxide (N_2O). These reactions can only occur under anoxic conditions.

Wetlands retain nitrogen by sorption of NH_4^+ to organic material in soils and incorporation into biomass. They also remove nitrogen through denitrification which reduces nitrate (NO_3^-) to nitrogen gas (N_2). Nitrogen cycling in freshwater wetlands is dominated by the release of nitrogen gas.[153] Thus, freshwater wetlands serve as sinks for nitrogen, reducing nitrogen loads contributed to other surface waters.[154] In anoxic wetland environments the nitrogen pool is dominated by ammonium. This can be especially the case in wetlands contaminated with chloride salts because cation replacement will tend to release ammonium that is adsorbed to organic matter and clay particles. Ammonium is soluble in water and can diffuse or be transported into oxic areas of the wetland. In oxic areas, nitrification mediated by bacteria converts ammonium to nitrite (NO_2^-) and then to NO_3^-. These ions are also soluble in water and can diffuse or be transported into anoxic areas of the wetland. Here nitrate serves as the substrate for bacterially mediated denitrification, which converts nitrate to nitrogen gas.

Additions of chloride and salinization may affect nitrogen cycling in wetlands. Nitrification decreases with exposure to salt water.[155] Soil nitrifying bacteria are sensitive to salinity. One study found that their activity

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[150] *W. Stumm and J. Morgan,* Aquatic Chemistry: Chemical Equilibria and Rates in Natural Waters (third edition), *Wiley, New York, 1996.*

[151] *Herbert et al. 2015,* op. cit.

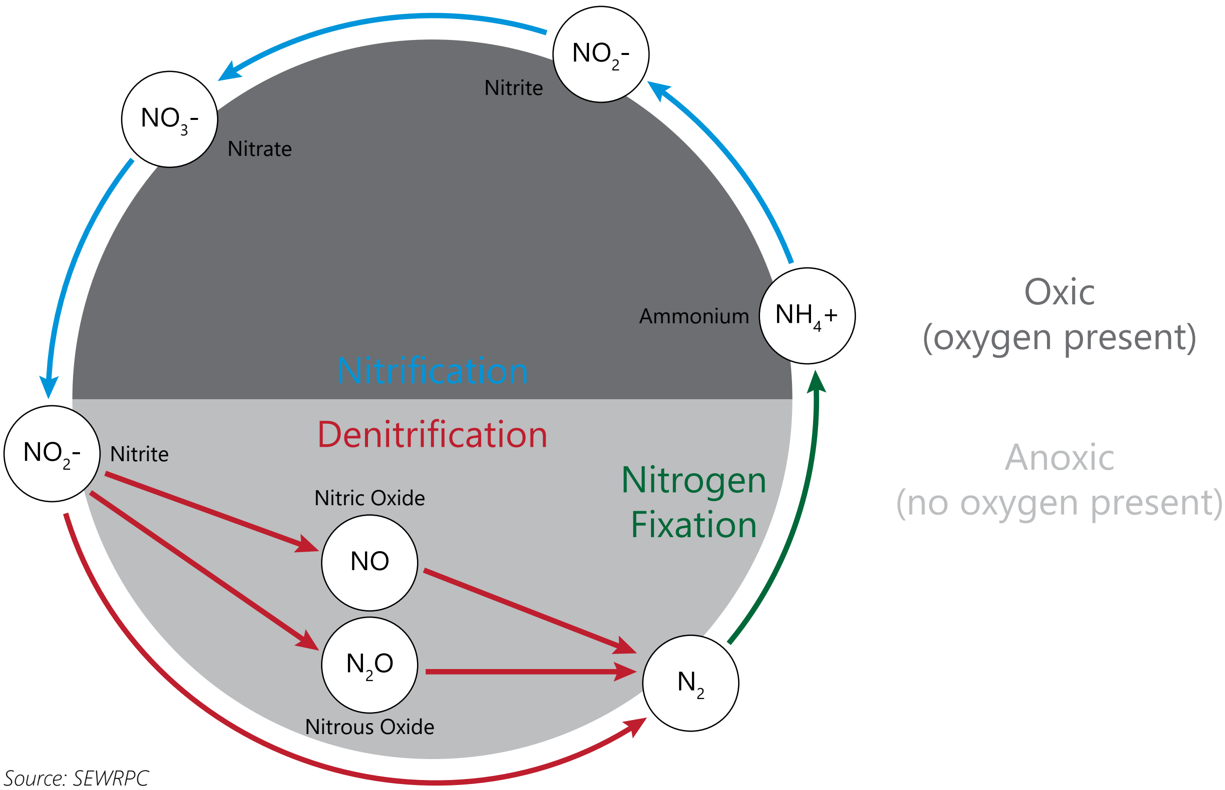
[152] *N. Brady and R. Weil,* Elements of the Nature and Properties of Soils, *Pearson Prentice Hall, New Jersey, 2004.*

[153] *S.B. Joye and J.T. Hollibaugh, "Influence of Sulfide Inhibition of Nitrification on Nitrogen Regeneration in Sediments,"* Science, *270:623-625, 1995.*

[154] *J.B. Zedler, "Wetlands at Your Service: Reducing Impacts of Agriculture at the Watershed Scale,"* Frontiers in Ecology and the Environment, *1:65-72, 2003.*

[155] *S. Rysgaard, P. Thastum, T. Dalsgaard, P.B. Christensen, and N.P. Sloth, "Effects of Salinity on* NH_4^+*, Adsorption Capacity, Nitrification, and Denitrification in Danish Estuary Sediments,"* Estuaries, *22:21-30, 1999; G. Noe, K. Drauss, B.G. Lockaby, W. Conner, and C. Hupp, "The Effect of Increasing Salinity and Forest Mortality on Soil Nitrogen and Phosphorus Mineralization in Tidal Freshwater Forested Wetlands,"* Biogeochemistry, *114:225-244, 2013.*

Figure 2.17
The Nitrogen Cycle



Source: SEWRPC

is significantly reduced at NaCl concentrations equal to or greater than 0.25 mg/l.[156] Reduced nitrification activity decreases the nitrate available for denitrification. Increased ionic strength also interferes with the enzymes responsible for denitrification.[157] Suppression of denitrification may increase the potential for generation of nitrous oxide (N_2O), a powerful greenhouse gas.[158]

Effects on Carbon Cycling

Wetlands are major sinks for carbon. It has been estimated that wetland soils contain 45-70 percent of all terrestrial carbon.[159] The accumulation of carbon in wetland soils can play an important role in reducing the concentrations of greenhouse gases in the atmosphere and mitigating climate change.[160] By making metals more available, salinization of wetlands can increase the concentrations of electron acceptors used by bacteria in their energy metabolism. This could potentially stimulate the production and release of carbon dioxide through increased microbial breakdown of organic matter.[161]

[156] *S.M. Green, R. Machin, and M.S. Cresser, "Effect of Long-Term Changes in Soil Chemistry Induced by Road-Salt Applications on N-Transformations in Roadside Soils,"* Environmental Pollution, *152:20-31, 2008.*

[157] *C. Glass, and J. Silverstein, "Denitrification of High-Nitrate, High-Salinity Wastewater,"* Water Research, *33:223-229, 1999; Hale and Groffman 2006,* op. cit.

[158] *Herbert et al. 2015,* op. cit.

[159] *S. Mitra, R. Wassmann, and P.L. Vlek, "An Appraisal of Global Wetland Area and Its Organic Carbon Stock,"* Current Science, *88:25-35, 2005.*

[160] *E. Mcleod, G.L. Chmura, S. Bouillon, R. Salm, M. Björk, C.M. Duarte, C.E. Lovelock, W.H. Schlesinger, and B.R. Silliman, "A Blueprint for Blue Carbon: Toward an Improved Understanding of the Role of Vegetated Coastal Habitats in Sequestering CO_2,"* Frontiers in Ecology and the Environment, *9:552-560, 2011.*

[161] *Herbert et al. 2015,* op. cit.

Anaerobic respiration in wetlands is the largest natural source of methane to the atmosphere.[162] The effects of chloride and salinization on methane production and release in wetlands is not fully understood. Some studies have found that high salt concentrations can decrease the size of the soil microbial community and the rate of methanogenesis.163 Other studies suggest that NaCl concentrations on the order of 13,000 mg/l may be needed to decrease the rate of methane production.[164] Other evidence suggests that salinization may increase the rates of methane production and release from wetlands. As discussed in the section on impacts of chloride and chloride salts on soil and sediment, additions of chloride salt may make nickel more available in wetland environments. Since nickel ions are a required cofactor for the enzymes needed for methanogenesis, increases in nickel concentrations could lead to increases in methane production. In addition, contamination of wetland sediments with salts can increase the growth of microbial mats at the sediment-water interface. Mats could lead to a reduction in pH and elevated concentrations of cations which can increase the amount of anaerobic respiration, potentially leading to increased production and release of methane from the sediments.[165]

2.8 SUMMARY OF THE PHYSICAL AND CHEMICAL IMPACTS OF CHLORIDE SALTS ON THE NATURAL ENVIRONMENT

Several natural and human sources can introduce chloride salts into the environment. Because chloride is highly soluble in water, it will move with water through the environment. This means that chloride can travel through the environment along many different pathways and may pass through or reside in several different environmental compartments.

Introduction of chloride and chloride salts into the environment can lead to a number of physical and chemical impacts on the natural environment. Some impacts are caused by the chloride itself. Others are caused by the cation associated with chloride, especially sodium. These impacts include:

- Chloride is not decomposed, chemically altered, or removed from water by natural processes
- Chloride salts lower the freezing point of water
- Chloride can accumulate in soil, groundwater, and lakes, serving as a reservoir capable of contributing chloride to other parts of the environment
    - Chloride accumulation can lead to delays in the environmental response to reduced inputs of chloride
- Addition of chloride salts can lower the solubility of gases in water and wetland soils
    - Reduced gas solubility can reduce the amount of time available for processing of gases in soils, leading to higher emissions of nitrous oxide and methane which are greenhouse gases
- Additions of chloride salts can promote release of dissolved organic carbon compounds from streambed and lakebed sediments
    - Release of these compounds can reduce water transparency and the depth to which light penetrates into water, reducing the total amount of photosynthesis in the waterbody

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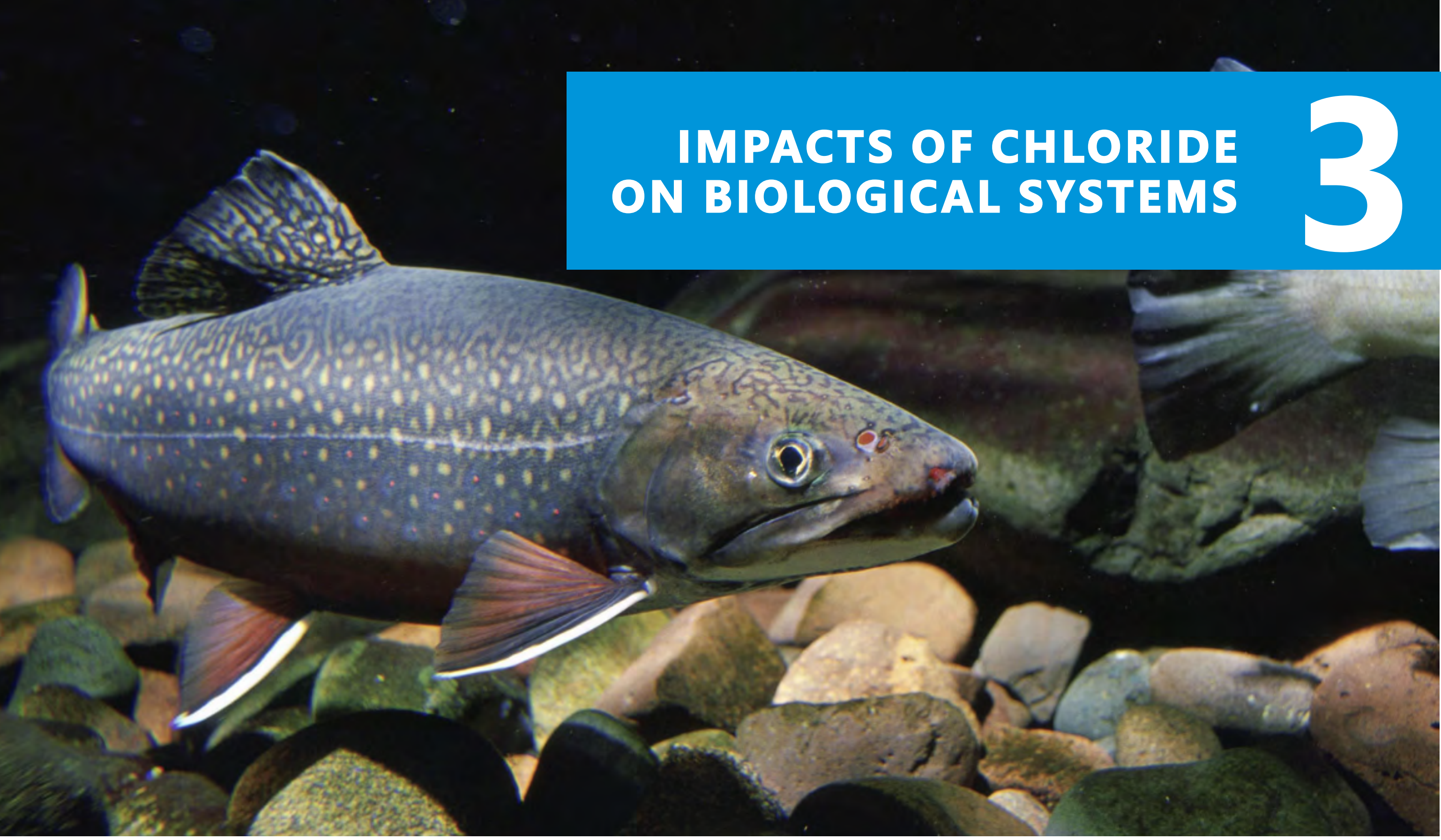
[162] *E. Matthews and I. Fung, "Methane Emission from Natural Wetlands: Global Distribution, Area, and Environmental Characteristics of Sources,* Global Biogeochemical Cycles, *1:61-86, 1987*.

[163] *P. Pattnaik, S.R. Mishra, K. Bharati, S.R. Mohanty, N. Sethunathan, and T.K. Adhya, "Influence of Salinity on Methanogenesis and Associated Microflora in Tropical Rice Soils,"* Microbiological Research, *155:215-220, 2000.*

[164] *L.G Chambers, K.R. Reddy, and T.Z. Osborne, "Short-Term Response of Carbon Cycling to Salinity Pulses in a Freshwater Wetland,"* Soil Science Society of America Journal, *75:2,000-2,007, 2011.*

[165] *Kim and Koretsky 2013,* op. cit.

- Addition of chloride salts increases the density of water
    - Increased water density can disrupt seasonal mixing of lakes, leading to shallower mixing depths or a lack of mixing
    - Disruption of mixing can cause reduced oxygen concentrations in the lake hypolimnion leading to anoxia which can result in numerous chemical and biological effects including release of metals and nutrients from sediment, generation of methane, alterations is solubility of substances, and reductions in the suitability of the hypolimnion as habitat for organisms
- Increases in the concentration of chloride salts can affect nitrogen cycling
    - Chloride salts can reduce rates of denitrification of nitrate to nitrogen gas in debris jams
    - Chloride salts can lead to decreased conversion of ammonium to nitrate in wetlands, making less nitrate available for conversion to nitrogen gas
    - Altered nitrogen cycling can result in accumulation nitrogen nutrients in wetlands and their export to other waters and an increased potential for nitrous oxide generation
- Additions of chloride to wetland soils can alter cycling of sulfur and iron leading to release of phosphorus
- Sodium ions from sodium chloride can displace other cations such as calcium, magnesium, ammonium, iron, aluminum, and potassium from negatively changed clay and humus particles, and in soil and rock
    - Displacement of divalent and multivalent cations that link clay and humus particles together by sodium can degrade soil structure because sodium ions are unable to link these particles together
    - Degradation of soil structure by sodium reduces the size of soil aggregates and can result in compaction of soil, reduced water infiltration into soil, reduced water retention, and adverse impacts to plants
    - Cation displacement by sodium ions can mobilize heavy metals and metalloids from soil and sediment which can have adverse effects on organisms, promote methane release from wetlands, and result in impacts to human health



IMPACTS OF CHLORIDE ON BIOLOGICAL SYSTEMS 3

Credit: Eric Engbretson, U.S. Fish and Wildlife Service

3.1 INTRODUCTION

Good environmental quality is important for the protection of natural systems. Changes in the quality of the environment can cause stresses that impact plants, animals, and other organisms. If these changes are great enough, they can cause major changes in the biological systems of an area. Releases of pollutants into the environment can cause these changes, potentially altering biological systems.

As noted in previous chapters of this report, concentrations of chloride salts and the associated salinity and specific conductance have been increasing in surface waters, both in the Southeastern Wisconsin Region and much of the nation.[166] Chloride salts have also been introduced into other parts of the environment. These chloride related increases have the potential to impact and alter ecological systems. Such effects might impact several levels of biological organization including individual organisms, populations of individual species, biological communities, and ecosystems.

This Chapter presents the findings of a literature review of the impacts of chloride salts on biological systems. It discusses the effects of chloride on organisms, biological communities, and ecosystems. It does not address the impact of chloride on human health. Those impacts are discussed in Chapter 5 of this report.

3.2 EFFECTS ON ORGANISMS

Increased concentrations of chloride salts in the environment can adversely affect organisms. At the most extreme level, exposure to high enough concentrations of chloride can lead to the death of organisms. The concentration causing death differs for different types of organisms, reflecting differences in their biology. Exposure to lower concentrations of chloride salts can result in sublethal impacts to organisms such as effects on their growth, reproduction, and physiology.

[166] *See for example, Richard C. Lathrop, "Chloride and Sodium Trends in the Yahara Lakes,* Research Management Findings, *No.12, Wisconsin Department of Natural Resources, June 1998; S.R. Corsi, L.A. De Cicco, M.A. Lutz, and R.M. Hirsch, "River Chloride Trends in Snow-Affected Urban Watersheds: Increasing Concentrations Outpace Urban Growth Rate and Are Common Among All Seasons,"* Science of the Total Environment,*508:488-497, 2015; and J.A. Thornton, T.M. Slawski, and H. Lin, "Salinization: The Ultimate Threat to Temperate Lakes, with Particular Reference to Southeastern Wisconsin (USA),"* Chinese Journal of Oceanology and Limnology, *33:1-15, 2015.*

This section reviews the effects of chloride salts on organisms. It includes discussion of acute and chronic toxicity. This section also discusses sublethal effects that different groups of organisms may experience from exposure to chloride.

This chapter and Appendix B of this report present results from field and experimental studies addressing impacts of chloride salts, salinity, and specific conductance on almost 200 different species and other taxa of organisms. This reflects the species that have been examined in the scientific literature for impacts from chloride salts. Of these species, 57 percent are found within Wisconsin. In addition, another 27 percent of the organisms belong to genera which are found in Wisconsin.

Toxicity

Toxicity is the ability of a substance or a mixture of substances to cause adverse effects to organisms. The types of adverse effects can differ depending on the toxic substance, the organism exposed, and the level of exposure. Examples of adverse effects caused by toxic substances include:

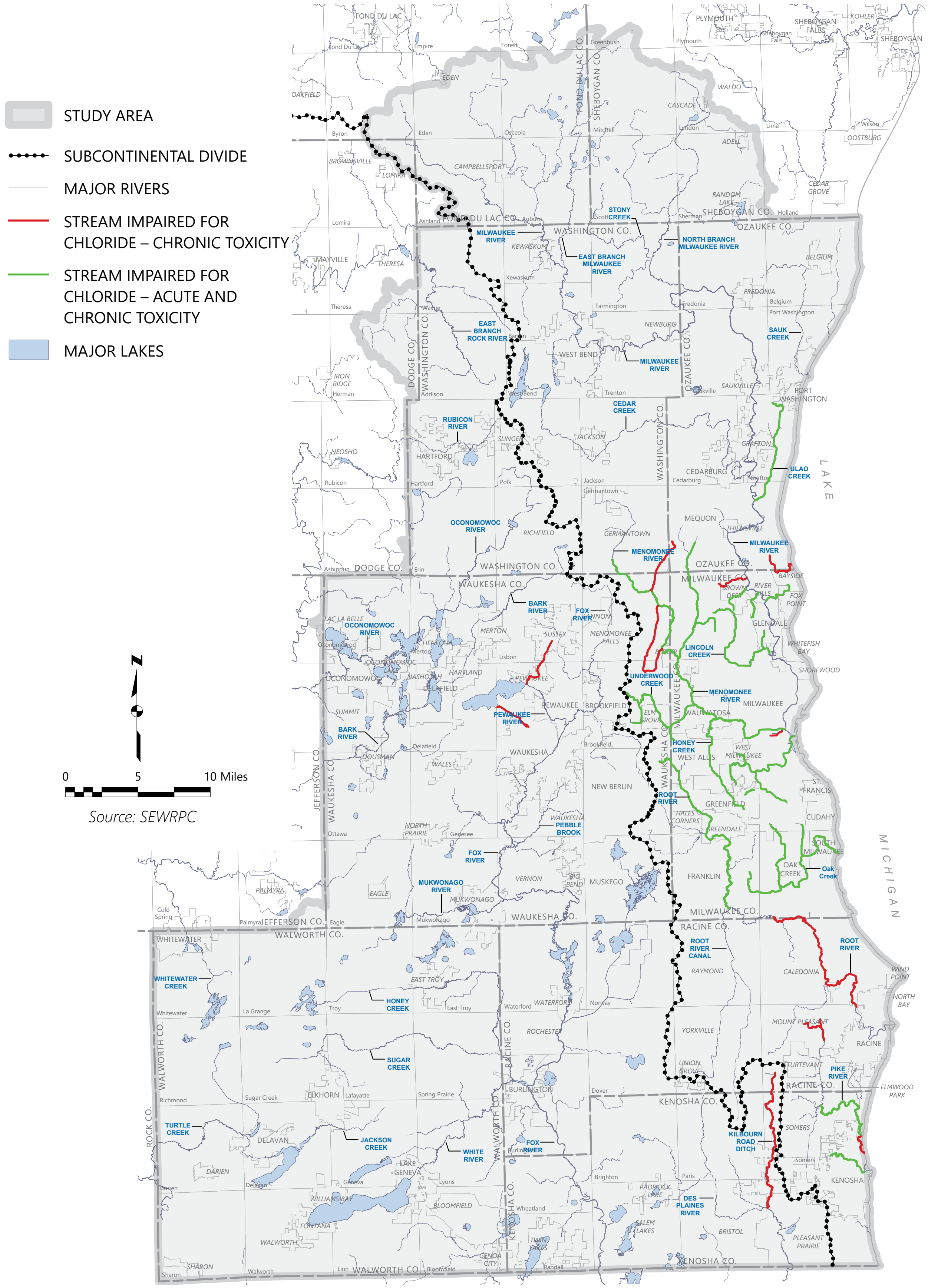
- Reduced somatic and population growth rates
- Reduced adult size
- The presence of developmental abnormalities
- Reduced rates of reproduction including lower rates of egg production, smaller clutch sizes, and lower hatching rates
- Altered behavior such as reduced rates of feeding, reduced swimming speeds, or changes in the amount of time spent on certain activities
- Death

Several factors can influence the type and severity of the effects of exposure to a toxic substance. The level of exposure or dose that an organism receives is a major factor affecting the impacts of a toxin. Higher doses often produce more severe adverse effects. In fact, some substances are non-toxic at lower doses, but become toxic at higher levels. The level of exposure that aquatic organisms are exposed to in water is often expressed as the concentration of the toxic substance in water. The manner of exposure to the toxic substance can also affect the type and severity of the substance's impacts. For instance, a toxic substance may produce different effects depending on whether it is ingested or absorbed through the skin. The number and duration of exposures can also affect the impacts of a toxic substance. Acute toxicity occurs when adverse effects result from a single or small number of exposures over a short period of time. Chronic toxicity occurs when adverse effects result from repeated or constant exposure over a longer period. Finally, environmental factors such as temperature and the presence of other substances can affect toxicity. The specific factors that affect the toxicity of chloride will be discussed later in this Chapter.

The State of Wisconsin has promulgated two surface water quality criteria for chloride, an acute toxicity criterion and a chronic toxicity criterion. These criteria are meant to ensure adequate protection of aquatic organisms from toxic effects. Under the acute toxicity criterion, the maximum daily concentration of chloride is not to exceed 757 milligrams per liter (mg/l)[167] more than once every three years. Under the chronic toxicity criterion, the four-day average of maximum daily concentration of chloride is not to exceed 395 mg/l more than once every three years. Surface waterbodies that exceed either of these criteria are considered impaired under Section 303(d) of the Federal Clean Water Act. In 2022, 35 waterbodies in southeastern Wisconsin were listed as impaired due to exceeding either or both chloride toxicity criteria. The impaired waterbodies are shown on Map 3.1 and listed in Table 3.1.

[167] *Acronyms and abbreviations used in this report are defined in Appendix A.*

Map 3.1
Waterbodies Impaired for Chloride: 2022



Source: SEWRPC

Table 3.1
Waterbodies Listed as Impaired Due to Chloride in Southeastern Wisconsin: 2022

Name	WBIC[a]	County	Extent (River mile)[b]	Impairment: Acute Toxicity	Impairment: Chronic Toxicity	Listing Date
Beaver Creek	20000	Milwaukee	0.00-2.65	--	X	2020
Brown Deer Creek	19700	Milwaukee	0.00-2.30	X	X	2018
Burnham Canal	3000042	Milwaukee	0.00-1.05	--	X	2018
Butler Ditch	18100	Waukesha	0.00-2.85	--	X	2020
Crestwood Creek	19450	Milwaukee	0.00-1.35	X	X	2020
Dousman Ditch	17100	Waukesha	0.00-2.50	X	X	2022
Fish Creek	44700	Ozaukee, Milwaukee	0.00-3.38	--	X	2018
Honey Creek	16300	Milwaukee	0.00-8.96	X	X	2018
Indian Creek	19600	Milwaukee	0.00-2.63	X	X	2018
Kilbourn Road Ditch	736900	Racine	0.0-14.3	--	X	2022
Kinnickinnic River	15100	Milwaukee	5.49-9.93	X	X	2018
Kinnickinnic River	15100	Milwaukee	3.16-5.49	X	X	2014
Kinnickinnic River	15100	Milwaukee	0.00-3.16	X	X	2022
Lilly Creek	18400	Waukesha	0.00-4.70	--	X	2016
Lincoln Creek	19400	Milwaukee	0.0-9.7	X	X	2014
Little Menomonee River	17600	Ozaukee, Milwaukee	0.0-9.0	X	X	2016
Meadow Brook Creek	772300	Waukesha	0.00-3.14	--	X	2018
Menomonee River	16000	Washington, Waukesha, Milwaukee	0.00-24.81	X	X	2018
Mitchell Field Drainage Ditch	14800	Milwaukee	0.0-2.3	X	X	2020
North Branch Oak Creek	14900	Milwaukee	0.0-5.7	X	X	2018
North Branch Pike River	1900	Racine, Kenosha	5.23-7.87	--	X	2018
Nor-X-Way Channel	18450	Ozaukee, Washington, Waukesha	0.0-4.9	--	X	2020
Noyes Creek	17700	Milwaukee	0.00-3.54	X	X	2020
Oak Creek	14500	Milwaukee	0.00-13.32	X	X	2014
Pewaukee River above Pewaukee Lake	771800	Waukesha	0.00-.45	--	X	2020
Pike Creek	1200	Kenosha	0.00-3.69	X	X	2016
Pike River	1300	Kenosha	1.45-9.50	X	X	2016
Pike River	1300	Kenosha	0.00-1.45	--	X	2016
Root River	2900	Waukesha, Milwaukee	25.80-43.69	X	X	2014
Root River	2900	Milwaukee, Racine	5.82-20.48	--	X	2022
South 43rd Street Ditch	15900	Milwaukee	0.00-1.16	X	X	2022
Southbranch Creek	3000073	Milwaukee	0.00-2.36	X	X	2018
South Branch of Underwood Creek	16800	Waukesha, Milwaukee	0.00-1.11	X	X	2018
Ulao Creek	21200	Ozaukee	0.0-8.6	X	X	2016
Underwood Creek	16700	Waukesha, Milwaukee	0.00-8.54	X	X	2018
Unnamed Tributary to North Branch Pike River	2450	Racine	0.00-0.58	--	X	2016
Wilson Park Creek	15200	Milwaukee	0.0-3.5	X	X	2018
Zablocki Park Creek	5036633	Milwaukee	0.0-0.9	X	X	2020

[a] *The WBIC is a unique identification number for a waterbody assigned and used by the Wisconsin Department of Natural Resources.*

[b] *River mile is measured upstream from the confluence with whatever the waterbody drains into.*

Source: Wisconsin Department of Natural Resources

Acute Toxicity of Chloride

Acute toxicity is often measured by the deaths of test organisms. For freshwater aquatic organisms, acute toxicity is often expressed as the LC50. This is the concentration at which 50 percent of the organisms die over the duration of the test.[168] A higher LC50 indicates lower toxicity to the organism, while a lower LC50 indicates greater sensitivity to the toxin. An LC50 value represents a substantial toxic effect to organism populations. While LC50 values are useful measures of acute toxicity, they do not represent thresholds below which concentrations are safe or harmless in aquatic habitats. It should be kept in mind that appreciable acute toxic effects can be expected to occur at concentrations that are lower than the LC50. In addition, appreciable acute toxicity effects may occur over shorter periods of time than the test period associated with a particular LC50. Because of this, it is important to recognize that evaluations of toxicity that utilize LC50s as an indicator of toxicity refer to concentrations at which substantial incidences of toxic effects are likely to be occurring, as opposed to concentrations at which toxic effects begin to appear. Figure 3.1 shows several aquatic organisms that are commonly used in acute toxicity testing. These organisms are used for testing because they are relatively easy to maintain in a laboratory setting and their biology has been well-studied.

The LC50s cited in the discussion that follows reflect the toxicity of individual, relatively pure chloride salts. The chlorides that are introduced into the environment in forms such as deicers, water softening salts, and fertilizers often contain other substances. For example, commercial deicers contain trace amounts of metals, anticaking ingredients, corrosion inhibitors, and other substances. One study found that sodium chloride-based deicers contained trace amounts of copper, zinc, cyanide, and sulfate.[169] Some of these other substances can cause acute toxicity in aquatic organisms at low concentrations. Unless otherwise stated, toxic effects related to the presence of these substances are not reflected in the LC50 values in the discussion in this section. Because of this, the LC50 values may not reflect the possibility of cumulative effects of mixtures of toxic substances. Despite these caveats, LC50 values are useful for comparing the effects of a toxic substance on different species, populations, or strains of organisms.

Tables 3.2 through 3.5 summarize reported LC50s for chloride for zooplankton, macroinvertebrates, fish, and amphibian species. The tables present results for several exposure times; however, for most groups the majority of the results come from 96-hour (four-day) acute toxicity tests. This is in keeping with standard toxicological procedures. The test results are presented in terms of the concentration of chloride that the organisms were exposed to. This was done to facilitate comparison of the toxicological data to estimates of chloride concentrations in surface waterbodies and to the State acute toxicity criterion for fish and aquatic life. Results from individual toxicity tests are given in Appendix B. In the discussion that follows, the LC50s will be expressed in terms of chloride concentrations.

Some patterns are apparent in values presented in Tables 3.2 through 3.5. There is considerable variation in LC50 values, even for the same species in the same duration test. For example, at test durations ranging between 24 hours and 96 hours, the reported LC50s for the water flea *Daphnia magna* range over two to three orders of magnitude (see Table 3.2). This wide range may be due to several factors, including differences in test conditions, differences in the cation associated with chloride, genetic variation within species, and differences among statistical techniques used to calculate the LC50 value from the raw toxicology data. Potential causes of the wide range of toxic impacts are discussed in the section on factors that can affect the toxicity of chloride.

For individual species, lower LC50s are generally associated with longer periods of exposure. Examples among macroinvertebrates that show this clearly include the brown dun mayfly (*Ameletus* sp.), the pond snail (*Lymnaea* sp.), and the European physa snail (*Physa heterostropha*) (see Table 3.3). This is also shown in the lowest reported LC50s for each test duration for the wood frog (*Lithobates sylvatica*) (see Table 3.5). The lowest reported LC50 values for wood frogs came from the same study and were conducted on tadpoles in the same developmental

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[168] *It should be noted that other measures of the level of acute toxicity are sometimes used. For example, the LC10 and LC25 endpoints reflect the concentrations at which 10 percent and 25 percent, respectively, of organisms die during the test.*

[169] *B. Mussato and T. Guthrie, "Anti-icers: Chemical Analysis and Toxicity Test Results," Prepared for Insurance Corporation of British Columbia, 2000, cited in Colorado Department of Transportation, "Evaluation of Selected Deicers Based upon a Review of the Literature," Report No. CDOT-DTD-R-2001-15, October 30, 2001.*

Figure 3.1
Aquatic Organisms Used in Acute Toxicity Testing

Water Flea (*Ceriodaphnia dubia*)

Water Flea (*Daphnia magna*)

Sludge Worm (*Tubifex tubifex*)

Scud (*Hyalella azteca*)

Fathead Minnow (*Pimephales promelas*)

Wood Frog Tadpole (*Lithobates sylvatica*)

Source: Wikimedia Commons

Table 3.2
LC50 Ranges Reported for Chloride for Zooplankton Species at Different Exposure Durations[a]

Species	LC50 (mg chloride/l)			
	24-hour	48-hour	72-hour	96-hour
Cladocerans				
Ceriodaphnia dubia	300-2,050	275-1,836	--	1,400-1,596
Ceriodaphnia sylvestrii	--	971	--	--
Daphnia ambigua	--	1,213	--	--
Daphnia hyalina	--	5,303	--	--
Daphnia carinata	--	--	--	1,062-1,400
Daphnia longispina	--	1,504-1,759	--	--
Daphnia magna	132-4,704	84-4,004	56-485	14-4,071
Daphnia pulex	1,652	1,099-1,239	--	1,470
Daphnia similis	--	328-566	--	--
Pseudosida ramosa	--	9-838	--	--
Copepods				
Cyclops abyssorum prealiinus	--	12,395	--	--
Eudiaptomus padanus padanus	--	7,092	--	--
Nitocra sinipes	--	406	--	--
Ostracods				
Cypris subglobasa	--	611-1,365	--	--
Rotifers				
Brachionus calyciflorus	804-2,220	--	--	--

Note: References for sources are given in Appendix B.

[a] *Ranges include toxicities of chloride salts commonly used for deicing, water softening, and agriculture including sodium chloride (NaCl), calcium chloride ($CaCl_2$), potassium chloride (KCl), and magnesium chloride ($MgCl_2$).*

Source: SEWRPC

stage under the same test conditions.[170] It should be noted that the inherent toxicity of a substance like chloride does not change with longer exposure. Instead, longer exposures give the toxin more opportunity to cause damage. As a result, lethal toxic effects occur at lower concentrations with longer exposures.[171]

Tables 3.2 through 3.5 also show that different groups of organisms have different sensitivities to chloride toxicity. In general, adult fish tend to be less sensitive to acute toxicity from chloride than zooplankton, macroinvertebrates, or amphibians. Among macroinvertebrates, mayflies (Order Ephemeroptera) appear to be more sensitive to acute toxicity from chloride than other insects such as flies (Order Diptera) or caddisflies (Order Trichoptera). Similar variation is seen within these larger groups of organisms. With a 96-hour LC50 of 425 mg/l, the gray quill mayfly *Callibaetis coloradensis* appears to be particularly sensitive to acute chloride toxicity. Along the same lines, caddisflies in the genus *Hydropsyche* appear to be much less sensitive to acute chloride toxicity in 96-hour tests than other species of caddisflies.

Many of the LC50s shown in Tables 3.2 through 3.5 are lower than Wisconsin's acute toxicity criterion of 757 mg/l. This is seen in several groups such as zooplankton including species of *Ceriodaphnia, Daphnia*, and *Nitocra*; macroinvertebrates including some mayflies (*Centroptilium triangulifer)*, snails (*Lymnaea* sp., and *Melanoides tuberculate)*, and bivalves (*Dreissena polymorpha, Epioblasma torulosa, Lampsilis fascicola, and Lampsilis siliquoidea)*; fish including golden shiners (*Notemigonus crysolucas)* and young walleye (*Stizostedion vitreum*), rainbow trout (*Onchorhynchus mykiss*), and sanger (*Stizostedion canadense*); and amphibians including tadpoles of wood frog (*Lithobates sylvatica*) and boreal toad (*Bufo boreas*). While these LC50s derive from laboratory studies, the results suggest that some species may be experiencing substantial toxic effects at chloride concentrations below Wisconsin's acute toxicity criterion. This in turn suggests that the current acute toxicity criterion in Wisconsin might not be fully protective of aquatic life.

[170] *A.L. Copan,* Acute Toxicity of Deicing Compounds and Personal Care Products to Early Amphibian Life Stages, *Master's Thesis, Saint Mary's University, Halifax, Nova Scotia, Canada, 2016.*

[171] *D.W. Connell, Q.J. Yu, and V. Verma, "Influence of Exposure Time on Toxicity—An Overview,"* Toxicology, *355-356:49-53, 2016.*

Table 3.3
LC50 Ranges Reported for Chloride for Macroinvertebrate Species at Different Exposure Durations[a]

Species	LC50 (mg chloride/l)			
	24-hour	48-hour	72-hour	96-hour
Annelida				
Lumbriculus variegatus (California blackworm)	--	--	--	3,100
Tubifex tubifex (Sludge worm)	1,441-1,928	1,077-1,567	--	778-6,008
Crustacea-Amphipoda				
Gammarus pseudolimnaeus (Scud)	--	--	--	4,670
Gammarus sobaegensis (Scud)	--	2,171-2,766	--	--
Hyalella azteca (Mexican Scud)	--	--	--	1,382-3,947
Crustacea-Branchiopoda				
Streptocephalus probocideus (Sudanese fairy shrimp)	889-3,961	--	--	--
Crustacea-Isopoda				
Lirceus fontinalis (Pillbug)	--	--	--	2,970
Insecta-Diptera				
Chironomus attenuatus (Midge)	--	--	--	4,026
Chironomus dilutus (Midge)	--	--	--	5,867
Cricotopus trifascia (Midge)	--	--	--	3,149
Culex sp. (Mosquito)	6,369	6,222	--	--
Gluptotendipes tokunagai (Midge)	--	2,355-2,690	--	--
Insecta-Ephemeroptera				
Ameletus sp. (Brown dun mayfly)	>4,853	4,222	3,118	2,505
Baetis tricaudatus (Blue-winged olive mayfly)	--	3,233-3,300	--	--
Callibaetis coloradensis (Gray quill mayfly)	--	--	--	425
Caridina dentriculata denticulata (Sawtooth caridina mayfly)	--	9,801-11,580	--	--
Centroptilum triangulifer[b] (Triangle small minnow mayfly)	--	400-931	--	1,062
Cloeon dipterum (Common wetland mayfly)	--	3,073-3,766	--	--
Ecdyonurus levis (Western ginger quill mayfly)	--	3,876-3,943	--	--
Hexagenia limbata (Giant mayfly)	--	--	--	1,456-2,822
Isonychia bicolor (Mahogany dun mayfly)	--	--	--	1,880
Neocloeon triganulifer (Triangle small minnow mayfly)	--	--	--	1,062
Stenonema rubrum (Flatheaded mayfly)	--	1,517	--	--
Insecta-Trichoptera				
Anabolia nervosa (Brown sedge caddisfly)	--	--	4,255	--
Hydropsyche betteni (Spotted sedge caddisfly)	--	--	--	8,073
Hydropsyche sp. (Caddisfly)	--	--	--	5,459
Hydroptila angusta (Varicolored microcaddisfly)	--	--	--	3,352
Lepidostoma sp. (Little brown sedge caddisfly)	--	--	--	3,640
Limnephilus stigma (Summer flier sedge caddisfly)	--	--	4,255	--
Pycnopsyche guttifer (Great autumn brown sedge caddisfly)	--	--	--	2,140
Pycnopsyche lepida (Great autumn brown sedge caddisfly)	--	--	--	2,140
Mollusca-Basommatophora				
Gyraulus parvus (Planorbid snail)	--	--	--	3,009-3,078
Lymnaea sp. (Pond snail)	923-2,865	709-2,055	484-2,113	523-1,644
Melanoides tuberculate (Red-rimmed melania snail)	--	333	--	--
Physa gyrina (Tadpole physa snail)	--	--	--	2,480
Physa heterostropha (European physa snail)	3,354	3,112	2,966	447-2,863
Mollusca-Bivalvia				
Anodonta anatina (Duck mussel)	2,505	--	--	--
Corbicula fluminea (Asian clam)	--	--	--	2,162->22,581
Dreissena polymorpha (Zebra mussel)	49-66	70-71	--	--
Elliptio complanata (Eastern elliptio mussel)	1,620	1,353	--	--
Epioblasma torulosa (Northern riffle shell mussel)	244	--	--	--
Lampsilis cardium (Plain pocketbook mussel)	817	--	--	--
Lampsilis fascicola (Wavy-rayed lampmussel)	113-1,559	1,055	--	2,414

Table continued on next page.

Table 3.3 (Continued)

Species	LC50 (mg chloride/l)			
	24-hour	48-hour	72-hour	96-hour
Mollusca-Bivalvia (continued)				
Lampsilis siliquoidea (Fat mucket mussel)	168-1,430	340-2,166	--	1,595-2,766
Ligumia recta (Black sandshell mussel)	764	2,275	--	1,523
Musculium transversum (Long fingernail clam)	--	--	--	1,930
Obliquaria reflexa (Threehorned wartyback mussel)	--	>972	--	--
Ptychobranchus fasciolaris (Kidneyshell mussel)	3,416	--	--	--
Sphaerium simile (Fingernail clam)	--	--	--	740-1,100
Villosa constricta (Notched rainbow mussel)	1,674	1,574	--	--
Villosa delumbis (Eastern creekshell mussel)	2,008	2,202	--	3,173
Nematoda				
Caenorhabditis elegans (Round worm)	28,367	--	--	--

Note: References for sources are given in Appendix B.

[a] *Ranges include toxicities of chloride salts commonly used for deicing, water softening, and agriculture including sodium chloride (NaCl), calcium chloride ($CaCl_2$), potassium chloride (KCl), and magnesium chloride ($MgCl_2$).*

[b] *This taxon is also referred to as* Neocloeon triangulifer *in older literature.*

Source: SEWRPC

Chronic Toxicity of Chloride

Acute toxicity is not the only toxic effect associated with chloride. While chronic exposures to chloride can result in the deaths of organisms, these exposures have also been shown to produce a variety of sublethal effects in different aquatic organisms. These effects fall into several categories including growth and development, reproduction, and behavior.

Chronic exposure to chloride salts can have several impacts on the growth and development of organisms. The simplest may be that chronic exposure can slow organismal growth. For example, one study found that chronic exposure to high levels of salinity reduced the rate of somatic growth in two mayfly species and one midge species.[172] Reduced growth rates resulting from chronic exposure to chloride salts has also been observed as slower growth of portions of an organism, such as plant roots[173] or mussel shells,[174] and lower weights attained after a standard period of growth.[175] Some developmental effects may be more subtle. For instance, chronic exposure to chloride salts can alter the duration of the larval period of some organisms.[176] This can lead to delayed maturity[177] or failure to metamorphose or enter the next life history stage.[178] Finally, chronic exposure to chloride salts can result in organisms having developmental abnormalities.[179]

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[172] *K.L. Hassell, B.J. Kefford, and D. Negegoda, "Sub-lethal and Chronic Salinity Tolerances of Three Freshwater Insect:* Cloeon *sp. and* Centroptilum *sp. (Ephemeroptera: Baetidae) and* Chironomus *sp. (Diptera: Chironomidae),"* Journal of Experimental Biology, *209:4,024-4,034, 2006.*

[173] *A. .Joutti, E. Schultz, P. Pessala, T Nysten and P. Hellsten, "Ecotoxicity of Alternative Deicers,"* Journal of Soils and Sediments, *3:269-372, 2003.*

[174] *R.B. Bringolf, W.G. Cope, C.B. Eads, P.R. Lazaro, M.C. Barnhart, and D. Shea, "Acute and Chronic Toxicity of Technical-Grade Pesticides to Glochidia and Juveniles of Freshwater Mussels,"* Environmental Toxicology and Chemistry, *26:2,086-2,093, 2007.*

[175] *J.A. Buckley, K.P. Rustagi, and J.D. Laughlin, "Response of* Lemnia minor *to Sodium Chloride and a Statistical Analysis of Continuous Measurements for EC50 and 95% Confidence Limits Calculation,"* Bulletin of Environmental Contamination and Toxicology, *57:1,003-1,008, 1996.*

[176] *S. Collins,* Toxicity of Deicing Salt Components to Early Amphibian Life Stages, *Master's Thesis, Saint Mary's University, Halifax, Nova Scotia, Canada, March 2010.*

[177] *E.C. Freitas, and O. Rocha, "Effects of Sodium and Potassium on Life History Parameters of Freshwater Cladoceran* Pseudosida ramose,*"* Journal of the Brazilian Society of Ecotoxicology, *7:85-91, 2012.*

[178] *Collins 2010,* op. cit.

[179] *S.J. Collins and R.W. Russell, "Toxicity of Road Salt to Nova Scotia Amphibians,"* Environmental Pollution, *157:320-324, 2009.*

Table 3.4
LC50 Ranges Reported for Chloride for Fish Species at Different Exposure Durations[a]

Species	LC50 (mg chloride/l)			
	24-hour	48-hour	72-hour	96-hour
Anguilla rostrata (American eel)	--	--	--	10,900-13,085
Carassius auratus (Goldfish)	8,341	--	--	4,453
Catla catla (Major carp)	4,550	--	--	3,021
Cirrhinius mrigalo (Mrigal carp)	4,550	--	--	3,021
Gambusia affins (Mosquito fish)	4,745-13,931	1,993-13,189	--	437-12,260
Ictalurus punctatus (Channel catfish)	3,489	342	--	--
Labeo rohita (Rohu carp)	163-4,550	38-6,524	27-6,448	19-6,370
Lepomis macrochirus (Bluegill)	2,615-8,568	--	--	956-7,864
Molliensia latipinna (Sailfin mollie)	--	10,067	--	--
Notemigonus crysolucas (Golden shiners)	388	--	--	--
Oncorhynchus mykiss (Rainbow trout)	566-3,334	766	--	6,030-12,371
Pimephales promelas (Fathead minnow)	452-5,023	433-4,665	4,640	418-6,570
Stizostedion canadense (Sanger)	238	--	--	--
Stizostedion vitreum (Walleye)	344	--	--	--

Note: References for sources are given in Appendix B.

[a] *Ranges include toxicities of chloride salts commonly used for deicing, water softening, and agriculture including sodium chloride (NaCl), calcium chloride ($CaCl_2$), potassium chloride (KCl), and magnesium chloride ($MgCl_2$).*

Source: SEWRPC

Table 3.5
LC50 Ranges Reported for Chloride for Amphibian Species at Different Exposure Durations[a]

Species	LC50 (mg chloride/l)[b]			
	24-hour	48-hour	72-hour	96-hour
Ambystoma maculatum (Spotted salamander)	--	--	--	1,178
Bufo americanus (American toad)	--	--	--	3,928
Bufo boreas (Boreal toad)	3,271	3,271	--	483
Eurycea bislineata (Northern two-lined salamander)	--	--	--	5,505
Lithobates sylvatica (Wood frog)[b,c]	248-5,532	147-5,421	112-5,392	86-5,295
Microhyla ornata (Ornate narrow-mouthed frog)	2,378-3,932	--	--	672-4,203
Pseudacris crucifer (Spring peeper)	--	--	--	2,830
Rana clamitans (Green frog)	--	--	--	2,421-3,109

Note: References for sources are given in Appendix B.

[a] *Ranges include toxicities of chloride salts commonly used for deicing, water softening, and agriculture including sodium chloride (NaCl), calcium chloride ($CaCl_2$), potassium chloride (KCl), and magnesium chloride ($MgCl_2$).*

[b] *The wide range of some LC50s may reflect studies using different life stages of the species or tests conducted under different conditions.*

[c] *This species is also referred to as* Rana sylvatica *in some older literature.*

Source: SEWRPC

Chronic exposure to chloride salts can also affect reproduction and several different outcomes have been reported. Chronic exposure to sodium chloride has been reported to inhibit fertilization in some fish species.[180] Chronic exposure to chloride salts has also been reported to reduce hatching success in amphibians.[181] Chronic exposure to chloride salts can also lower the number of offspring produced by a female.[182] This can occur in a number of ways including reducing the number of eggs produced per female, the number of live offspring produced per female, or the number of eggs produced in a single brood.[183] Chronic exposure to chloride salts can also have more subtle effects on reproduction. For example, chronic chloride exposure can result in an increase in the age at which members of a species first reproduce.[184] This tends to lower the total number of offspring that a female produces over her lifetime.

Chronic exposure to chloride can affect behavior in ways that reduce the viability of the affected organisms. For instance, a laboratory study showed that over longer exposures, the level of activity in European grass frog (*Rana temporaria*) tadpoles decreased with increasing sodium chloride concentration.[185] At high concentrations, the tadpoles moved shorter distances and more slowly than at low concentrations. Since low activity levels in tadpoles have been associated with a lower probability of escaping from predators and may limit the foraging capabilities of the tadpoles,[186] this effect could reduce the viability of amphibian populations exposed to chloride in some environments. Other organisms have been reported to reduce feeding when exposed to higher concentrations of chloride salts. For example, *Anodonta anatina*, a freshwater mussel that feeds by filtering particles out of the water, reduces its filtration activity under higher sodium chloride concentrations.[187] Similarly, when exposed to higher concentrations of sodium chloride, freshwater golden clams (*Corbicula fluminea*) closed their shells.[188] This reduces feeding and allows metabolic wastes to build up which can ultimately reduce the viability of the clams.

Chronic toxicity can have many different effects on organisms including lethal and sublethal effects. In addition, different types of organisms can experience different toxic effects from chloride. Sublethal impacts of chloride salts on organisms that are due to or likely due to chronic toxicity are discussed in the sections of this Chapter on the effects of chloride on freshwater and terrestrial organisms.

Factors that Affect the Toxicity of Chloride

As previously mentioned, laboratory data shows that there can be considerable variation in the LC50s for chloride for an individual species from a test of a given duration (see Tables 3.2 through 3.5). This variation reflects differences in test conditions and may be due to environmental factors related to test conditions, other constituents of the salts tested, or biological factors related to the organisms tested. These are described in more detail in the following sections.

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[180] *U. Mahrosh, M. Kleiven, S. Meland, B.O. Rosseland, B. Salbu, and H.-C. Teien, "Single and Multiple Stressor Effect of Road Deicing Salt (NaCl) and Copper (Cu) to Fertilization and Early Development Stages of Atlantic Salmon (*Salmo salar*) Alevins from Hatching to Swim-up,"* Journal of Environmental Sciences, *66:368-378, 2018.*

[181] *Collins 2010,* op. cit.

[182] *A.L. Copan, 2016,* op. cit.

[183] *E.C. Freitas, and O. Rocha, "Acute and Chronic Effects of Sodium and Potassium on the Tropical Freshwater Cladoceran* Psuedosida ramose," Ecotoxicology, *20:88-96, 2011.*

[184] *Frietas and Rocha 2012.* op. cit.

[185] *M. Denoël, M. Bichot, G.F. Ficetola, J. Delcourt, M. Ylieff, P. Kestermont, and P. Poncin, "Cumulative Effects of Road De-Icing Salt on Amphibian Behavior,"* Aquatic Toxicology, *99:275-280, 2010.*

[186] *T.B. Watkins, "Predator-Mediated Selection on Burst Swimming Performance in Tadpoles of the Pacific Tree Frog,* Pseudacris regilla" Physiological Zoology, *69:154-167, 1996; C, Tepelitsky, S. Laenet, J.-P. Lena, N. Mermet, E. Malet, and P. Joly, "Escape Behavior and Ultimate Causes of specific Induced Defenses in an Anuran Tadpole,"* Journal of Evolutionary Biology, *18:180-190, 2005.*

[187] *J.T. Hartmann, S. Beggel, K. Auerswald, B.C. Stoeckle, and J. Geist, "Establishing Mussel Behavior as a Biomarker in Ecotoxicology,"* Aquatic Toxicology, *170:279-288, 2016.*

[188] *K.D. Coldsnow and R.A. Relyea, "Toxicity of Various Road-Deicing Salts to Asian Clams (*Corbicula fluminea*),"* Environmental Toxicology and Chemistry, *37:1,839-1,845, 2018.*

Environmental Factors

Several environmental factors can affect the toxicity of chloride. While these factors can be controlled in laboratory toxicity tests, they often vary in nature. As a result, they can alter the impact of chloride on populations of organisms. These factors include temperature, water hardness, the presence of other chemicals, and the nutritional status of the organisms.

Temperature

The water temperature at which aquatic organisms are exposed to chloride salts can influence the toxicity of chloride. For example, Table 3.6 shows LC50 values for four species of mayfly larvae exposed to sodium chloride (NaCl) for 96 hours at seven different water temperatures in a laboratory study.[189] In three species, the maximum LC50, or the greatest tolerance of chloride, occurs at an intermediate temperature. The temperature at which greatest tolerance occurs differs among the species, with *Neocloeon triangulifer* showing its highest tolerance at a relatively cold temperature and *Leptophlebia cupida* showing its highest tolerance at a much warmer temperature. Highest tolerance at an intermediate temperature may not have been observed in *Procloeon fragile* because the toxicity of chloride was not tested at the two lowest temperatures in the study. At temperatures higher than the temperature at which maximum tolerance to chloride was observed, the toxicity of chloride increased rapidly as temperature increased. At the highest temperature tested, the LC50 chloride concentrations represented between 3 and 27 percent of the concentrations at the temperatures where each species showed maximum tolerance, indicating that the toxicity of chloride had increased substantially with the increase in temperature.

Above the temperature of maximum chloride tolerance, the LC50s for sodium chloride for the mayfly species shown in Table 3.6 decreased exponentially as temperature increased. The amount of decrease is consistent with a general pattern in observed in the acute toxicity of many substances in which an 18°F increase in temperature often leads to a two-to-four-fold reduction in the LC50, conforming to a general pattern in which the toxicity of many substances increases substantially with increased in temperature.[190]

It should be noted that most toxicity tests for chloride and chloride salts are conducted at temperatures between 63°F and 77°F, which are recommended as standard temperatures for toxicity testing. Low water temperatures during the winter may reduce the frequency of chloride-related toxicity events below what would be expected with winter deicing activities. Despite this, chloride concentrations during the winter can still get high enough to cause toxic effects even when accounting for the effects of low temperatures.[191]

This effect of temperature on the toxicity of chloride has implications for the well-being of aquatic organisms in southeastern Wisconsin under potential future conditions. There has been a long-term trend toward increasing chloride concentrations in many waterbodies of the Southeastern Wisconsin Region.[192] Climate projections for southeastern Wisconsin indicate that average air temperatures the Region will be warmer in the future, with average air temperatures at the end of the century being five to 10 degrees Fahrenheit warmer than current conditions. This change depends on the carbon emissions scenario used to produce the projection.[193] Projected air temperatures are likely to increase water temperatures in many waterbodies in the Region. For example, projections generated by the U.S. Geological Survey's FishVis decision support tool predict that water temperatures in all modeled streams of the Oak Creek watershed will increase by up to 3.6°F by the end of the century.[194] These projected temperature increases may be further exacerbated by the loss of shade along the Oak Creek Parkway due to the ongoing decline of the ash tree canopy

[189] *J.K. Jackson and D.H. Funk, "Temperature Affects Acute Mayfly Responses to Elevated Salinity: Implication for Toxicity of Road De-icing Salts,"* Philosophical Transactions of the Royal Society, Series B, *374:20150084, doi: 10.1098/rstb.2018.0081, 2018.*

[190] *F.L. Mayer Jr., and M.R. Ellersieck, "Experiences with Single-Species Tests for Acute Effects on Freshwater Animals,"* Ambio, *17:367-375, 1988.*

[191] *Jackson and Funk 2018,* op. cit.

[192] *SEWRPC Technical Report No. 63,* Chloride Conditions and Trends in Southeastern Wisconsin, *in preparation.*

[193] *Wisconsin Initiative on Climate Change Impacts,* Wisconsin's Changing Climate: Impacts and Solutions for a Warmer Climate, *2021.*

[194] *J.S Stewart, S.A. Covert, N.J. Estes, S.M. Westenbroek, D. Krueger, D.J. Wieferich, M.T. Slattery, J.D. Lyons, J.E. McKenna, Jr, D.M. Infante, and J.L. Bruce,* FishVis, A Regional Decision Support Tool for Identifying Vulnerabilities of Riverine Habitat and Fishes to Climate Change in the Great Lakes Region, *U.S. Geological Survey Scientific Investigations Report No. 2016-5124, 2016.*

Table 3.6
LC50s for Four Mayfly Species Exposed to Sodium Chloride for 96 hours at Different Water Temperatures

Temperature (°F)	Triangle Small Minnow Mayfly (*Neocloeon triangulifer*) (mg Cl^-/l)	Fragile Small Minnow Mayfly (*Procloeon fragile*) (mg Cl^-/l)	Cream Cahill Mayfly (*Maccaffertium modestum*) (mg Cl^-/l)	Early Brown Spinner Mayfly (*Leptophlebia cupida*) (mg Cl^-/l)
41.0	9,655	--	10,086	--
45.5	10,462	--	10,152	7,236
50.0	6,719	6,874	10,439	5,429
54.5	5,101	4,115	11,908	7,792
59.0	2,573	3,239	8,368	7,808
68.0	2,755	767	4,588	2,760
77.0	364	766	3,216	1,656

Source: J.K. Jackson and D.H. Funk, "Temperature Affects Acute Mayfly Responses to Elevated Salinity: Implication for Toxicity of Road De-icing Salts," Philosophical Transactions of the Royal Society, Series B, *374:20150081, doi: 10.1098/rstb.2018.0081, 2018*

and subsequent spread of invasive buckthorn and reed canary grass.[195] Should these predicted water temperature increases occur, it could result in the incidence and severity of chloride toxicity impacts being greater than what would be expected otherwise.

Water Hardness

The hardness of the water in which aquatic organisms are exposed to chloride can affect the toxicity of chloride. Hardness is an indicator of the mineral content of water and measures the combined concentrations of ions of calcium, magnesium, and several other metals. The main components of hardness are calcium and magnesium ions. Because the relative concentrations of the constituents of hardness can vary, measurements of hardness are often reported as an equivalent concentration of milligrams per liter of calcium carbonate (mg/l as $CaCO_3$).

Table 3.7 shows an example of the effect of hardness on the acute toxicity of chloride from a laboratory study.[196] In 48-hour toxicity tests using the water flea *Ceriodaphnia dubia*, the LC50 increased with increasing hardness, indicating that the water fleas were less sensitive to chloride in harder water. The same study observed a similar effect of hardness on acute chloride toxicity in 96-hour tests using the freshwater clam, *Sphaerium simile*, and the annelid sludge worm, *Tubifex tubifex*. The study did not observe a difference using the snail *Gyraulus parvus*; however, the range of hardness used in these tests was narrow, extending between 56 and 212 mg/l as $CaCO_3$.

The mechanism through which higher hardness reduces sodium chloride toxicity is not known. Calcium ions have been shown to reduce the permeability of cell membranes to both water and other ions. This has been shown in studies with fish[197] and invertebrates.[198] Such an effect may reduce passive diffusion of chloride into the cells of these animals or reduce the energy that they require to regulate their ionic content. Alternatively, the decrease in chloride toxicity that occurs with increasing hardness may be related to the maintenance of a tolerable ratio of cations within the organism rather than any mechanistic effect of hardness itself.[199]

[195] *SEWRPC Community Assistance Planning Report No. 330,* A Restoration Plan for the Oak Creek Watershed, *December 2021.*

[196] *D.J. Soucek, T.K. Linton, C.D. Tarr, A. Dickinson, N. Wickramanayake, C.G. Delos, and L.A. Cruz, "Influence of Water Hardness and Sulfate on the Acute Toxicity of Chloride to Sensitive Freshwater Invertebrates,"* Environmental Toxicology and Chemistry, *30:930-938, 2011.*

[197] *F.B. Eddy, "The Effect of Calcium on Gill Potentials and on Sodium and Chloride Fluxes in the Goldfish,* Carassium auratus," Journal of Comparative Physiology, *96:131-142, 1975; P. Pic and J. Maetz, "Role of External Calcium in Sodium and Chloride Transport in the Gills of Seawater-adapted* Mugil capito," Journal of Comparative Physiology B, *141:511-521, 1981; W.T.W. Potts and W.R. Flemming," The Effects of Prolactin and Divalent Ions on the Permeability to Water of* Fundulus kansae," Journal of Experimental Biology, *53:317-327, 1970.*

[198] *J.D. Robertson, "The Function and Metabolism of Calcium in the Invertebrata,"* Biological Reviews, *16:106-133, 1941.*

[199] *J.R.F. Elphick, K.D. Bergh, and H.C. Bailey, "Chronic Toxicity of Chloride to Freshwater Species: Effect of Hardness and Implications for Water Quality Guidelines,"* Environmental Toxicology and Chemistry, *30:239-246, 2011.*

Table 3.7
Acute Toxicity of Sodium Chloride (NaCl) to the Water Flea (*Ceriodaphnia dubia*) Exposed for 48 Hours at Different Levels of Water Hardness

Average Hardness (mg/l as $CaCO_3$)	Hardness Range (mg/l as $CaCO_3$)	Average Calcium Concentration (mg/l)	Average Magnesium Concentration (mg/l)	Average LC50 (mg/l Chloride)
28	25-30	5.3	2.3	977
47	44-49	10.8	4.8	861
96	95-96	20.9	9.3	1,249
187	180-194	42.0	18.7	1,402
388	375-400	81.8	36.9	1,589
565	560-570	123.0	56.1	1,779
796	792-800	170.5	77.3	1,836

Source: D.J. Soucek, T.K. Linton, C.D. Tarr, A Dickinson, N. Wickramanayake, C.G. Delos, and, L.A. Cruz, "Influence of Water Hardness and Sulfate on the Acute Toxicity of Chloride to Sensitive Freshwater Invertebrates," Environmental Toxicology and Chemistry, *30:930-938, 2011*

Many waterbodies in southeastern Wisconsin contain hard water. For example, a study of water quality in six watersheds of the Region found that average hardness ranged from 253 mg/l as calcium carbonate ($CaCO_3$) in the Kinnickinnic River to 374 mg/l as $CaCO_3$ in the Root River.[200]

Presence of Other Chemicals

The concentrations of other chemicals in the water may also affect the toxicity of chloride to aquatic organisms. Table 3.8 shows that the toxicity of chloride to the water flea *Ceriodaphnia dubia* increased slightly as the concentration of sulfate in the water increased.[201] A similar effect of chloride concentration on the toxicity of sulfate to both *Ceriodaphnia dubia* and the amphipod *Hyalella azteca* has been reported in which higher chloride concentrations resulted in lower LC50s for sulfate.[202] This suggests that the toxic effects of these two ions to these organisms are additive, with the magnitude of the total impact being equal to the sum of the individual effects of the ions.

The toxicity of chloride salts may sometimes increase with declining concentrations of other substances. Studies with the water flea *Daphnia magna* showed that the toxicity of both sodium chloride and calcium chloride increased as the concentration of dissolved oxygen in the water decreased.[203] This increase in toxicity likely reflects the organisms experiencing the combined effects of the two stressors.

Test Organism Nutritional Status

In general, the toxicity of a chemical to an aquatic organism is influenced by the availability of its food supply.[204] At the same concentration of the toxicant, LC50s and other toxicology endpoints show greater toxicity when food is less available or when organisms are under nutritional stress than at higher levels of food availability.

A laboratory study using a uniclonal hybrid of two *Daphnia* species found a strong positive linear relationship between the concentration of available food and the LC50 for chloride in 14-day toxicity tests.[205] The study also found similar linear relationships between food availability and chronic toxicity endpoints such as

[200] *SEWRPC Technical Report No. 39,* Water Quality Conditions and Sources of Pollution in the Greater Milwaukee Watersheds, *November 2007.*

[201] *Soucek et al. 2011,* op. cit.

[202] *D.J. Soucek, "Comparison of Hardness- and Chloride-Regulated Acute Effect of Sodium Sulfate on Two Freshwater Crustaceans,"* Environmental Toxicology and Chemistry, *26:773-779, 2007.*

[203] *E.J. Fairchild II,* Effects of Lowered Oxygen Tension on the Susceptibility of *Daphnia magna* to Certain Inorganic Salts, *Ph.D. Dissertation, Louisiana State University, Baton Rouge, Louisiana, 1954.*

[204] *E.H.W. Heugens, A.J. Hendrick, T. Dekker, N.M. van Straalen, and W. Admiraal, "A Review of the Effects of Multiple Stressors on Aquatic Organisms and Analysis of Uncertainty Factors for Use in Risk Assessment,"* Critical Reviews in Toxicology, *31:247-284, 2001.*

[205] *A.H. Brown and N.D. Yan, "Food Quantity Affects the Sensitivity of* Daphnia *to Road Salt,"* Environmental Science and Technology, *49:4,673-4,680, 2015.*

age at first reproduction, clutch size, total egg production, and growth rate. Similar food supply impacts were seen when the organisms were exposed to sodium chloride and calcium chloride, though at equivalent concentrations of chloride the LC50s were lower for calcium chloride than sodium chloride. The range of food levels used in this laboratory study spanned the ranges seen in lakes, including concentrations that are similar to those in oligotrophic, mesotrophic, and eutrophic lakes. The findings of the study suggest that organisms living in oligotrophic systems might be particularly vulnerable to the toxic effects from chloride.

Table 3.8
Acute Toxicity of Sodium Chloride (NaCl) to the Water Flea (*Ceriodaphnia dubia*) Exposed for 48 Hours at Different Concentrations of Sulfate (SO_4^{2-})

Average Sulfate Concentration (mg/l)	Range of Sulfate Concentrations (mg/l)	Average LC50 (mg/l Chloride)
26	23-28	1,356
55	50-60	1,489
112	107-117	1,317
234	229-239	1,357
472	461-482	1,154
712	694-729	1,192

Source: D.J. Soucek, T.K. Linton, C.D. Tarr, A Dickinson, N. Wickramanayake, C.G. Delos, and, L.A. Cruz, "Influence of Water Hardness and Sulfate on the Acute Toxicity of Chloride to Sensitive Freshwater Invertebrates," Environmental Toxicology and Chemistry, *30:930-938, 2011*

The relationship between the toxicity of chloride and the availability of food may reflect the impact of nutritional status on the ability of an organism to repair itself. An organism that is exposed to a toxicant such as chloride needs energy to fuel repair mechanisms and compensate for changes in osmotic balance.[206] The greater the exposure to the toxicant, the more energy, and thus the more food, the organism needs to counteract damage. Thus, the increased toxicity of chloride to *Daphnia* at low food levels may be the result of a decreased ability of the organism to pay the energy costs needed to repair itself at low food levels.

<u>Other Salt Ingredients and Impurities</u>

Other substances in chloride salts may affect their overall toxicity. Chloride salts produced for some uses are relatively pure. Examples of this include sodium chloride produced for use as table salt or water softener salt. Other chloride salts may include additives or impurities that can produce their own toxic effects. Examples of these include the cation associated with the chloride ion, chemicals added to a salt to prevent caking or to reduce the salt's corrosive effects, and impurities in the salt.

Cations

The cation associated with chloride can have a major effect on the toxicity experienced by organisms. Reviews of laboratory toxicity studies have found that magnesium chloride and calcium chloride are far more toxic to many aquatic organisms than sodium chloride and can produce impacts at lower concentrations.[207] For example, a review found that sodium chloride-based deicers have lower toxicity to rainbow trout (*Onchrhynchys mykiss*), the water flea *Ceriodaphnia dubia*, and the alga *Selenastrum capricornatum* than other chloride-based deicers such as calcium chloride and magnesium chloride and acetate-based deicers.[208] Most of the studies reviewed showed that magnesium chloride was particularly toxic to many organisms. The reviews found that the general order of toxicity of chloride salts from least toxic to most toxic is sodium chloride, calcium chloride, magnesium chloride, and potassium chloride. It is important to note that species differ in their tolerance to chloride associated with various cations and some deviate from the patterns discussed in the review articles. Table 3.9 shows that the relative toxicities experienced by freshwater golden clam *Corbicula fluminea* when exposed to different chloride salts follow the pattern described in the reviews. Tables 3.10 and 3.11 show that patterns of LC50s for chloride associated with different cations for the water flea *Daphnia magna,* and the diatom, *Nitzchia*, respectively are different than those seen in the freshwater golden clam.

[206] *H.J. Geyer, C.E. Steinberg, I. Scheunert, R. Brüggemann, W. Schütz, A. Kettrup, and K. Rozman, "A Review of the Relationship between Acute Toxicity (LC50) of g-Hexachorocyclohexane (g-HCH, Lindane) and Total Lipid Content of Different Fish Species,"* Toxicology, *83:169-179, 1993.*

[207] *D.A. Benoit, and C.E. Stephan,* Ambient Water Quality Criteria for Chloride, *U.S. Environmental Protection Agency EPA 440/5-88-001, February 1988; M. Evans and C. Frick,* The Effects of Road Salt on Aquatic Ecosystems, *National Water Research Institute Contribution Series No. 02-038, Saskatoon, Saskatchewan, Canada, 2001.*

[208] *B. Mussato and T. Guthrie 2000,* op. cit.

In addition to the cation associated with chloride, the toxicity of different chloride salts can be affected by the presence of other cations in the water. A laboratory study of the toxicity of major ions to the water flea *Ceriodaphnia dubia* found a complex relationship among the toxicities of different cations.[209] This study found that the toxicity of sodium ions and magnesium ions to this water flea decreased as the concentration of calcium ions in the water increased. In addition, the toxicity of potassium ions to this species decreased as the concentration of sodium ions increased. As with hardness, these relationships among the toxicities of different cations may be related to maintaining a tolerable internal ratio of cations;[210] however, the mechanisms responsible for toxicity appears to be different among salts with different cations.[211] The toxicity of potassium and magnesium salts may be primarily due to the toxicity of the cation. The toxicity of sodium salts appears to be due to both the toxicities of the cation and the anion. In *Ceriodaphnia dubia*, this appears to be related, at least in part, to osmotic stress caused by the salt. It is also likely that the toxicity of calcium salts is due to the cation; however, since the presence of calcium may ameliorate chloride toxicity, this is less certain.

Table 3.9
Acute Toxicity of Three Chloride Salts to the Asian Clam (*Corbicula fluminea*) Exposed for 192 Hours

Chloride Salt	LC50 (mg Cl^-/l)
Sodium chloride (NaCl)	10,069
Calcium chloride ($CaCl_2$)	2,235
Magnesium chloride ($MgCl_2$)	1,769

*Source: K.D. Coldsnow and R. Relyea, "Toxicity of Various Road-Deicing Salts to Asian Clams (*Corbicula fluminea*), *Environmental Toxicology, doi.org/10.1002.etc.4126, 2018*

Table 3.10
Acute Toxicity of Four Chloride Salts to the Water Flea (*Daphnia magna*) Exposed for 100 Hours

Chloride Salt	LC50 (mg Cl^-/l)
Magnesium chloride ($MgCl_2$)	2,595
Sodium chloride (NaCl)	1,889
Calcium chloride ($CaCl_2$)	415
Potassium chloride (KCl)	323

Source: B.F. Dowden and H.J. Bennett, "Toxicity of Selected Chemicals to Certain Animals," Journal of the Water Pollution Control Federation, *37:1,308-1,326, 1965*

Table 3.11
Acute Toxicity of Three Chloride Salts to the Diatom (*Nitzschia linearis*) Exposed for 120 Hours

Chloride Salt	LC50 (mg Cl^-/l)
Calcium chloride ($CaCl_2$)	2,000
Sodium chloride (NaCl)	1,474
Potassium chloride (KCl)	701

Source: R. Patrick, J.J. Cairns, and A. Scheier, "The Relative Sensitivity o Diatoms, Snails, and Fish to Twenty Common Constituents o Industrial Wastes," The Progressive Fish-Culturist, *30:137-140, 1968*

As previously noted, these comparisons of the effects of the cations associated with chloride are based on toxicity assessments conducted in the laboratory. An important caution to note in interpreting these toxic effects to organisms is that they do not account for any differences in how these compounds are used. For example, in a highway deicing situation it is possible that a more toxic salt may be used in lower amounts which might produce fewer toxic effects. The difference in the amount of chloride salts with different cations that are used should always be considered when evaluating potential toxic effects.

Anticaking Additives

When deicing salt is exposed to air with fluctuating humidity, it can form large clumps that make spreading difficult.[212] When the relative humidity exceeds about 70 percent, a brine solution forms on the surface of the salt crystals.[213] This brine evaporates when the relative humidity drops, causing the salt in the brine to recrystallize which causes the salt crystals to clump together.

[209] *D.R. Mount, R.J. Erickson, T.L. Highland, J.R. Hockett, D.J. Hoff, C.Y. Jenson, T.J. Norberg-King, K.N. Peterson, Z.M. Polaske, and S. Wisniewski, "The Acute Toxicity of Major Ion Salts to* Ceriodaphnia dubia*: I. Influence of Background Water Chemistry,"* Environmental Toxicology and Chemistry, *35:3,039-3,057, 2016.*

[210] *Elphick et al. 2011,* op. cit.

[211] *Mount et al. 2016,* op. cit.

[212] *H.W. Fiedelman,* Prussian Blue and Sodium Ferrocyanide Additives for Deicing Salt, *Report No. 4, 930-012, Morton Salt Company, Woodstock, Illinois, 1971.*

[213] *F. Gotzfried,* Ferrocyanides as Anticaking Agents in Road Salt, *German Salt Industry Association, Bonn, Germany, 1995.*

Anticaking agents are often added to deicing salts to prevent clumping. While chromate and phosphate compounds are occasionally added to deicing salts for this purpose, the most common additives consist of iron cyanide compounds that are either sprayed onto the salt crystals or added to the brine solutions used to manufacture deicing salts. These iron cyanide compounds include sodium ferrocyanide ($Na_4Fe(CN)_6$), also known as yellow prussiate of soda, and ferric ferrocyanide ($Fe(Fe_3(CN)_6)_3$), also known as Prussian blue. These substances reduce the solubility of sodium chloride in the moisture adsorbed to the deicer, reducing recrystallization of the salt as humidity drops.

When road salt is stored or applied, ferrocyanide anticaking agents will dissolve with the salt. As a result, surface waters adjacent to salt storage facilities or heavily salted highways can be contaminated with ferrocyanides. These compounds are relatively nontoxic;[214] however, exposure to light can induce ferrocyanides in water to dissociate to release free cyanide in the forms of hydrogen cyanide (HCN) and cyanide ions (CN^-).[215] Ultimately, all of the cyanide contained in the iron-cyanide compounds can be released as free cyanide[216] which is highly toxic.

Cyanide contamination has been reported in runoff from salt piles. One study found that concentrations of total cyanide in runoff from road salt piles ranged from below the limit of detection to 200 micrograms per liter (μg/l).[217] Total cyanide includes both ferrocyanides and free cyanide. The same study reported that concentrations of free cyanide in runoff from salt piles ranged from below the limit of detection to 96 μg/l.

Contamination of runoff with cyanide compounds can lead to contamination of surface waterbodies and groundwater. For example, a study found that concentrations of total cyanide in Lincoln Creek in the City of Milwaukee ranged from below the limit of detection to 130 μg/l.[218] This study did not assess concentrations of free cyanide in the Creek.

Free cyanide is highly soluble in water and highly toxic. It is readily taken up by aquatic organisms through skin and gills.[219] Free cyanide can cause both acute and chronic toxic effects in aquatic organisms. Geometric means of LC50s for freshwater animal species in 96-hour acute toxicity tests ranged between 59 and 330 μg CN^-/l.[220] Coldwater fish were the most sensitive species to acute cyanide toxicity. This was followed in order of decreasing toxicity, by warmwater fish, cladoceran zooplankton, and aquatic insects. While some exceptions have been reported, organisms receiving a sublethal acute dose of free cyanide generally recover because they are able to detoxify it by converting the cyanide ion to thiocyanate (SCN^-).[221]

Cyanide toxicity occurs because it interferes with cellular respiration. Cyanide binds to and inactivates cytochrome c oxidase, an important enzyme in respiration. This results in cellular hypoxia which leads to respiratory arrest and death. Cyanide does not bioaccumulate nor is it magnified through the food web.

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[214] *Agency for Toxic Substances and Disease Registry,* Toxicological Profile for Cyanide, *U.S. Department of Health and Human Services, July 2006.*

[215] *J.L. Meeussen, M.G. Keizer and F.A.M. de Haan, "Chemical Stability and Decomposition Rate of Iron Cyanide Complexes in Soil Solutions,"* Environmental Science and Technology, *26:511-516, 1992.*

[216] *D. Kuhn and T.C. Young, "Direct Photolysis of Hexacyanoferrate (II) Under Conditions Representative of Surface Waters,"* Chemosphere, *60:1,222-1,230, 2005.*

[217] *T. Ohno,* Determination of Levels of Free Cyanide in Surface and Ground Waters Affected by MDOT Salt Storage Facilities, *Maine Department of Transportation Technical Report 86 C, 1989.*

[218] *V. Novotny, D. Muehring, D.W. Smith, and R. Facey, "Impact of Urban Nonpoint Source Snowmelt on Receiving Waters," Paper Presented at the 70th Annual Water Environment Federation Conference, Chicago, Illinois, 1997.*

[219] *R. Eisler,* Cyanide Hazards to Fish, Wildlife, and Invertebrates: A Synoptic Review, *Biological Report No. 85, U.S. Fish and Wildlife Service, 1991.*

[220] *R.W. Gensemer, D.K. DeForest, A.J. Stenhouse, C.J. Higgins, and R.D. Cardwell, "Aquatic Toxicity of Cyanide," Chapter 14 In: D.A. Dzombak, R.S. Ghosh, and G.M. Wong-Chong, (editors),* Cyanide in Water and Soil: Chemistry, Risk, and Management, *Taylor & Francis, Boca Raton, Florida, 2006.*

[221] Ibid.

Chronic exposure to cyanide can also cause adverse effects in freshwater organisms. Chronic exposure to cyanide concentrations of 5-10 μg/l interfered with reproduction in trout and salmon.[222] Exposure to cyanide led to reduced egg production in fathead minnows.[223] Cyanide exposure also reduced the length of time over which yearling coho salmon were able to swim against a current.[224]

Table 3.12
Wisconsin's Water Quality Criteria for Free Cyanide (HCN and CN^-)

Criteria	Coldwater Systems	All Others
Acute Toxicity[a] (μg/l)	22.40	45.80
Chronic Toxicity[b] (μg/l)	5.22	11.47

[a] *The maximum daily concentrations of free cyanide is not to exceed the acute toxicity criterion more than once every three years.*

[b] *The four-day maximum concentration of free cyanide is not to exceed the chronic toxicity criterion more than once every three years.*

Source: Wisconsin Department of Natural Resources

The State of Wisconsin has established acute and chronic toxicity water quality criteria for free cyanide. These criteria are meant to ensure adequate protection of aquatic organisms from toxic effects and are shown in Table 3.12. Surface waterbodies that exceed either of these criteria are considered to be impaired under Section 303(d) of the Federal Clean Water Act. In 2022, no waterbodies in southeastern Wisconsin were listed as impaired for exceeding cyanide water quality standards.

Anti-Corrosion Additives

Corrosion inhibitors are added to some formulations of chemical deicers to reduce or prevent corrosion of metallic material that the deicers come into contact with. An analysis of the composition of 11 deicing compounds found that these additives mostly consist of organic compounds; however, the exact composition of some is not certain because of the proprietary nature of the formulations.[225] Some corrosion inhibitors are derived from sugar cane, sugar beets, corn, barley, or milk. Others contain organic amines such as triethanolamine. Many of these corrosion inhibitors are nontoxic, but some contain compounds that contribute to high biochemical oxygen demand (BOD). Reported levels of BOD associated with corrosion inhibitors in some deicers were as high as 83,000 milligram BOD per kilogram deicer (mg/kg).[226] Microbial decomposition of these compounds can reduce oxygen concentrations in surface waters, which can result in adverse impacts to aquatic organisms.

Decomposition of those corrosion inhibitors that contain amines can lead to the release of ammonia, which is toxic to aquatic organisms. The State of Wisconsin has promulgated acute and chronic water quality criteria for ammonia. The values of these are based on a formula that takes ambient pH and water temperature into account. This formula can be found in Chapter NR 105, Surface Water Quality Criteria and Secondary Values for Toxic Substances, of the *Wisconsin Administrative Code*.

Impurities

Some chloride salts used for deicing also contain various impurities. A review examining the chemical composition of 11 deicers found several contaminants that in high enough concentrations could have adverse effects on aquatic biota.[227] For example, the review found that a solid, sodium chloride-based deicer contained 0.29 mg/kg copper and 10 mg/kg zinc. Copper and zinc were also found in a brine deicer consisting of 23 percent sodium chloride, at concentrations of 0.78 mg/l and 2 mg/l, respectively.

[222] *A. Szabo, S.M. Ruby, F. Rogan, and Z. Amit, "Changes in Brain Dopamine Levels, Oocyte Growth and Spermatogenesis in Rainbow Trout,* Onchorhyncus mykiss, *Following Sublethal Cyanide Exposure,"* Archives of Environmental Contamination and Toxicology*: 21152-157, 1991.*

[223] *D.T. Lind, L.L. Smith, and S.J. Broderius, "Chronic Effects of Hydrogen Cyanide on the Fathead Minnow,* Journal of the Water Pollution Control Federation, *49:262-268, 1977.*

[224] *S.J. Broderius,* Determination of Molecular Hydrocyanic Acid in Water and Studies of the Chemistry and Toxicity to Fish of the Nickelcyanide Complex," *Master's Thesis, Oregon State University, Corvallis Oregon, 1970.*

[225] *M. Fischel,* Evaluation of Selected Deicers Based on a Review of the Literature, *Report No. CDOT-DTD-R-2001-15 to the Colorado Department of Transportation, October 30, 2001.*

[226] Ibid.

[227] Ibid.

The review also examined four magnesium chloride and calcium chloride deicers. High concentrations of arsenic, cadmium, copper, lead, and zinc were found in some magnesium chloride-based deicers. Some of these deicers also contained detectible amounts of chromium and barium, and others contained high levels of nitrates and/or ammonia. While the one calcium chloride-based deicer tested contained low concentrations of metals, it contained high concentrations of nitrates.

There have been relatively few studies of the combined toxic effects of chloride salts and heavy metals on organisms.[228] Depending on the underlying mechanisms of toxicity, chloride salts and heavy metals could have additive toxic effects in which the total effect is the sum of the effects of the two toxicants, synergistic effects in which the total effect is greater than the sum of the individual effects of the two toxicants, or antagonistic effects in which the total effect is less than the sum of the effects of the two toxicants. A study of salmon egg development found that the combined toxic effects of road salts and copper were more severe than the effects of each alone.[229] It is unknown if this result applies to other organisms.

Toxic impacts of heavy metal impurities in salts would be in addition to the impacts of any metals that were mobilized from soil or sediment by the salts. This topic was discussed in Chapter 2 of this Report.

The State of Wisconsin has promulgated acute and chronic water quality criteria for several of the metals that were detected in these deicer formulations. The criteria are based on formulas that take ambient water hardness into account. These formulas can be found in Chapter NR 105, Surface Water Quality Criteria and Secondary Values for Toxic Substances, of the *Wisconsin Administrative Code*.

Biological Factors

Biological factors can also affect the toxicity of chloride to organisms. Within a species, some developmental or life history stages may be more sensitive to the effects of chloride salts than others. In addition, genetic variation among organisms within a species may make some individuals more sensitive to and other individuals more tolerant of chloride salts.

Developmental Stage

The toxicity of chloride to many organisms is affected by the developmental or life history stage that the organism is in when it is exposed. Organisms in younger stages are often more sensitive to chloride than older individuals. For example, younger and smaller mayflies are more sensitive to toxic effects from sodium chloride than older individuals.[230] Similarly, juvenile water fleas in the species *Daphnia carinata* showed higher mortality rates than adults when exposed to chloride concentrations between 100 mg/l and 1,500 mg/l.[231]

The developmental stage during which aquatic vertebrates are exposed can have a major effect on the toxicity of chloride. Table 3.13 shows LC50s for five developmental stages of wood frog (*Lithobates sylvatica*) tadpoles that were

Table 3.13
Acute Toxicity of Sodium Chloride (NaCl) to Wood Frog (*Lithobates sylvatica*) Tadpoles Exposed for 72 Hours

Gosner Stage[a]	LC50 (mg Cl^-/l)
Stage 19	112
Stage 22	116
Stage 26	472
Stage 29	1,558
Stage 33	1,812

[a] *Gosner stages are stages in tadpole development. Higher numbered stages occur later in development.*

Source: A.L. Copan, Acute Toxicity of Deicing Compounds and Personal Care Products to Early Amphibian Life Stages *Master's Thesis, Saint Mary's University, Halifax, Nova Scotia, Canada, 2016.*

[228] *M.S. Schuler and R.A. Relyea, "A Review of the Combined Threats of Road Salts and Heavy Metals to Freshwater Systems,"* BioScience, *68:327-335, 2018.*

[229] *U. Mahrosh, M. Kleiven, S. Meland, B.O. Rosseland, B. Salbu. And H.-C. Teien, "Toxicity of Road Deicing Salt (NaCl) and Copper (Cu) to Fertilization and Early Development Stages of Atlantic Salmon* (Salmo salar*),"* Journal of Hazardous Materials, *280:331-339, 2014.*

[230] *J.M. Diamond, E.L. Winchester, D.G. Macker, and D. Gruber, "Use of the Mayfly* Stenonema modestum *(Heptageniidae) in Subacute Toxicity Assessment,"* Environmental Toxicology and Chemistry, *11:415-425, 1992.*

[231] *C.J. Hall and C.W. Burns, "Mortality and Growth Responses of* Daphnia carinata *to Increases in Temperature and Salinity,"* Freshwater Biology, *47:451-458, 2002.*

exposed to sodium chloride for 72 hours.[232] Gosner stages are levels in tadpole development. Stage 19 tadpoles are late-stage embryos that have begun to develop gills and tails. They still have a large yolk sac and have not begun to feed. Stage 33 tadpoles are actively feeding tadpoles. They have reduced gills and prominent hind limb buds. Toes are beginning to form on these limb buds. LC50s for wood frog tadpoles increase over the course of development indicating that that the older stages are less sensitive to chloride than the younger stages.

Early life history stages of freshwater fish are also more sensitive to chloride. Table 3.14 shows LC50s for four stages of Rohu carp (*Labeo rohita*) exposed to calcium chloride for 96 hours.[233] Spawn are larval fish that have hatched, but still have a yolk sac and do not feed. Fry are young fish that have absorbed their yolk sacs and have begun feeding. Calcium chloride is highly toxic to eggs of this fish species. As the fish develops after hatching, its tolerance of calcium chloride increases. Fingerling Rohu carp are much more tolerant of chloride than earlier life stages.

Table 3.14
Acute Toxicity of Calcium Chloride ($CaCl_2$) to Rohu Carp (*Labeo rohita*) Life Stages Exposed for 96 Hours

Life Stage	LC50 (mg Cl^-/l)
Eggs	19
Spawn	804
Fry	4,072
Fingerlings	6,300

*Source: A. Mallick, B.C. Mohapatra, and N. Sarangi, "Acute Toxicity of Calcium Chloride on Different Stages (Egg, Spawn, Fry and Fingerling) of Rohu (*Labeo rohita, *Hamilton)*," Research Journal of Animal, Veterinary and Fishery Science, *2:11-16, 2014*

Under some circumstances, the sensitivity of early life history stages of some aquatic organisms to chloride salts could reduce the viability of their populations. High chloride concentrations in a waterbody at times when these early life stages are present could reduce the number of individuals that successfully complete these stages. This could reduce or limit the recruitment of additional individuals into the adult population. Even though adults might be relatively tolerant of chloride, this could lead to an overall decline in the size, and ultimately the viability, of the aquatic organism population.

Genetic Variation

Genetic variation within a species may affect the sensitivity or tolerance of individuals to a toxic substance like chloride. This can be most clearly observed in clonal organisms. Such clonality occurs in cladoceran zooplankton. Water fleas, such as those in the genera *Daphnia* and *Ceriodaphnia* are cyclic parthenogens. Under normal conditions, they reproduce asexually.[234] The eggs that they produce contain exact duplicates of their mothers' genes. As a result of this, the population of a water flea species in a waterbody consists of several clones. The individuals within a clone are genetically identical to one another and would be expected to respond similarly to environmental stressors such as exposure to chloride.

Table 3.15 shows LC50s from laboratory studies of five different clones of the water flea *Daphnia longispina* that were exposed to sodium chloride for 48 hours.[235] The five clones show subtle differences in their sensitivity to chloride. The presence of these genetic differences in a population in the field can lead to changes in the population. Exposure to chloride could reduce the amount of genetic variation in a population by eliminating the most sensitive genotypes. This could have substantial effects on the population if it is also exposed to other toxic substances. Depending on the relationship of tolerance to the various toxicants, exposure to multiple toxic substances could lead to further reductions in genetic variation. The worst case would be that each toxic substance heavily impacts different clones. This could lead to extirpation of the species from the waterbody.[236]

[232] *A.L. Copan, 2016,* op. cit*.*

[233] *A. Mallick, B.C. Mohapatra, and N. Sarangi, "Acute Toxicity of Calcium Chloride on Different Stages (Egg, Spawn, Fry and Fingerling) of Rohu (*Labeo rohita*, Hamilton),"* Research Journal of Animal, Veterinary and Fishery Science*, 2:11-16, 2014.*

[234] *Sexual reproduction in water fleas occurs during periods of environmental stress and produces resting eggs which sink to the sediment and hatch the following spring.*

[235] *J. Leitao, R. Ribero, A.M.V.M. Soares, and I. Lopes, "Tolerance to Copper and Salinity in* Daphnia longispina*, Implications within a Climate Change Scenario,"* PLoS One, *8:e68702, 2013.*

[236] Ibid.

Effects on Freshwater Organisms

General Impacts of Salt on Freshwater Organisms

The addition of chloride salts and/or other salts alters the osmotic balance between freshwater organisms and their surrounding environment.[237] Normally, the concentration of salts in freshwater and soil water is much less than those within the cells and tissues of organisms. This means that freshwater organisms must have ways to keep salts from diffusing out of or compensate for salts diffusing out of their bodies and to keep water from diffusing into their bodies as a result of osmotic pressure generated by this concentration difference. Most freshwater organisms actively regulate their osmotic pressure.[238] This regulation has metabolic costs, and freshwater organisms expend energy to accomplish it.

Table 3.15
Acute Toxicity of Sodium Chloride (NaCl) to Different Clones of the Water Flea (*Daphnia longispina*) Exposed for 48 Hours

Clone	LC50 (mg Cl^-/l)
N116	1,729
E89	1,711
N91	1,698
E99	1,517
N31	1,504

Source: J. Leitao, R. Ribeiro, A.M.V.M. Soares, and I. Lopes, "Tolerance to Copper and Salinity in Daphnia Longispina*: Implications within a Climate Change Scenario,"* PLoS One, *8:e68702, 2013*

The osmotic balance freshwater organisms experience changes as the concentration of salts in water increases. When the concentration of salts in the water exceeds that in their bodies, organisms face the opposite challenge to the one described in the previous paragraph: they must have ways to keep salts from or compensate for salts diffusing into their bodies and keep water from diffusing out. Because they are adapted to environments in which their internal concentration of salt is higher than that of their environment, some aquatic organisms may lack mechanisms to accomplish these functions. In addition, these tasks also pose energy costs on the organisms that could reduce their viability. When external salinity gets too high, the osmoregulatory mechanisms of an organism may collapse.[239] This can lead to cellular damage. If the damage is severe enough, it can lead to death.

The above description of the impact of the effects of a change in salinity on freshwater organism osmotic balance is highly simplified. Osmoregulation is a complex process and involves regulation of many aspects of the organismal internal environment.[240] These aspects include the regulation of several properties such as total osmotic pressure, internal concentrations of individual ions, differences in ion concentrations within cells and the fluids surrounding cells, and internal acid-base balance.

Bacteria

Bacteria have important roles in aquatic, soil, and sediment communities. Some bacterial species degrade organic matter while other species mediate important processes such as nutrient cycling. In addition, bacteria serve as a food source for protozoa and some animals, including small zooplankton.

Several studies have reported the impacts of chloride salts on bacteria. Because of the difficulties identifying bacteria species in nature, most of these studies focused on bacterial communities as discussed below.

Chloride was found to have mixed effects on denitrifying bacteria. One study found that chloride concentrations of 2,000 mg/l and 5,000 mg/l inhibited denitrification in forested wetlands.[241] The same study found much less inhibition on denitrification in roadside wetlands that had historically been exposed

[237] *S.E.G. Findlay and V.R. Kelly, "Emerging Indirect and Long-term Road Salt Effects on Ecosystems,"* Annals of the New York Academy of Sciences, *1,223:58-68, 2011.*

[238] *M. Cañedo-Argüelles, B.J. Kefford, C. Piscart, R.B. Schäfer, and C.-J. Schulz, "Salinization of Rivers" An Urgent Ecological Issue,"* Environmental Pollution, *173:157-167, 2013.*

[239] Ibid.

[240] Ibid.

[241] *N.A. Lancaster, J.T. Bushey, C.R. Tobias, B. Song, and T.M. Vadas, "Impact of Chloride on Denitrification Potential in Roadside Wetlands,"* Environmental Pollution*, 212:216-223, 2016.*

to road salts. In addition, this study found that chloride concentrations of 2,000 mg/l and 5,000 mg/l increased the density of denitrifying bacteria in roadside wetlands. As discussed in Chapter 2 of this report, the increased ionic strength caused by salt introductions can suppress the bacterial enzymes responsible for denitrification.

Chloride salts can affect bacteria that are present in biofilms. In a microcosm study of biofilm communities, bacterial densities that were exposed to sodium chloride at concentrations of about 26 mg/l for 72 hours decreased relative to unexposed controls.[242] This occurred whether the exposure was constant or came in pulses that lasted 30 minutes. Oxygen consumption was also lower in the biofilm treatments exposed to sodium chloride than in the controls. Changes in salinity can affect the nature of a freshwater biofilm. The release of the extracellular substances that make up such films has been observed to increase with higher salinity.[243] This release may act to protect the cells and their processes.

Increased salinity may enhance the viability of some bacterial species in freshwater. For example, at specific conductance below 1,500 microSiemens per centimeter ($\mu S/cm$), the survival of *Escherichia coli* (*E. coli*) rose with increasing salinity in laboratory microcosms.[244] The increase in survival happened when the bacteria were exposed to either sodium chloride or a mixture of calcium chloride, magnesium chloride, and potassium chloride. Other experiments in the same study showed that *E. coli* exposed to magnesium chloride survived longer than those exposed to either sodium chloride or calcium chloride at the same levels of specific conductance. High salinities associated with brackish water and seawater are known to reduce the survival of *E. coli*.[245] Because of gaps in the available data, it is not clear where the thresholds for salt concentration and the survival of *E. coli* lie.[246] Given that the largest increase in survival occurred at the lower level of the range of specific conductance examined, these results suggest that small increases in salinity can dramatically affect bacterial water quality. Since *E. coli* is used as an indicator of fecal pollution and suitability of water for human contact, higher concentrations of chloride salts could lead to recreational use impairments of additional waterbodies by promoting survival of *E. coli*.

Algae

Algae is a term that refers to a diverse group of photosynthetic organisms. Many algal groups are only distantly related to each other. Forms of algae include prokaryotic single-celled, filamentous, and colonial cyanobacteria, which are also referred to as blue-green algae. Algae also include eukaryotic single-celled, filamentous, colonial, and multicellular forms in several different groups. Some groups, such as the red algae and brown algae are found mostly in marine environments, but others occur in freshwater environments and soils. Some examples of freshwater algae are shown in Figure 3.2.

Algae grow in several different places in the environment. Phytoplankton consists of unicellular, filamentous, and colonial algae that are suspended in the water column. Algal periphyton consists of unicellular, filamentous, and colonial algae that grow on surfaces in aquatic environments. Surfaces supporting algal growth include rocks, soft sediments, and plants. Macroalgae consist of multicellular algae that superficially resemble aquatic plants.

As primary producers, algae constitute part of the base of the food web. They are ubiquitous, abundant, and diverse. Because algae grow rapidly, they respond quickly to stresses in the environment and they are among the first organisms to respond to environmental changes.

[242] *J. Cochero, M. Licursi, and N. Gómez, "Effects of Pulse and Press Additions of Salt on Biofilms of Nutrient-rich Streams,"* Science of the Total Environment, *579:1,496-1,503, 2017.*

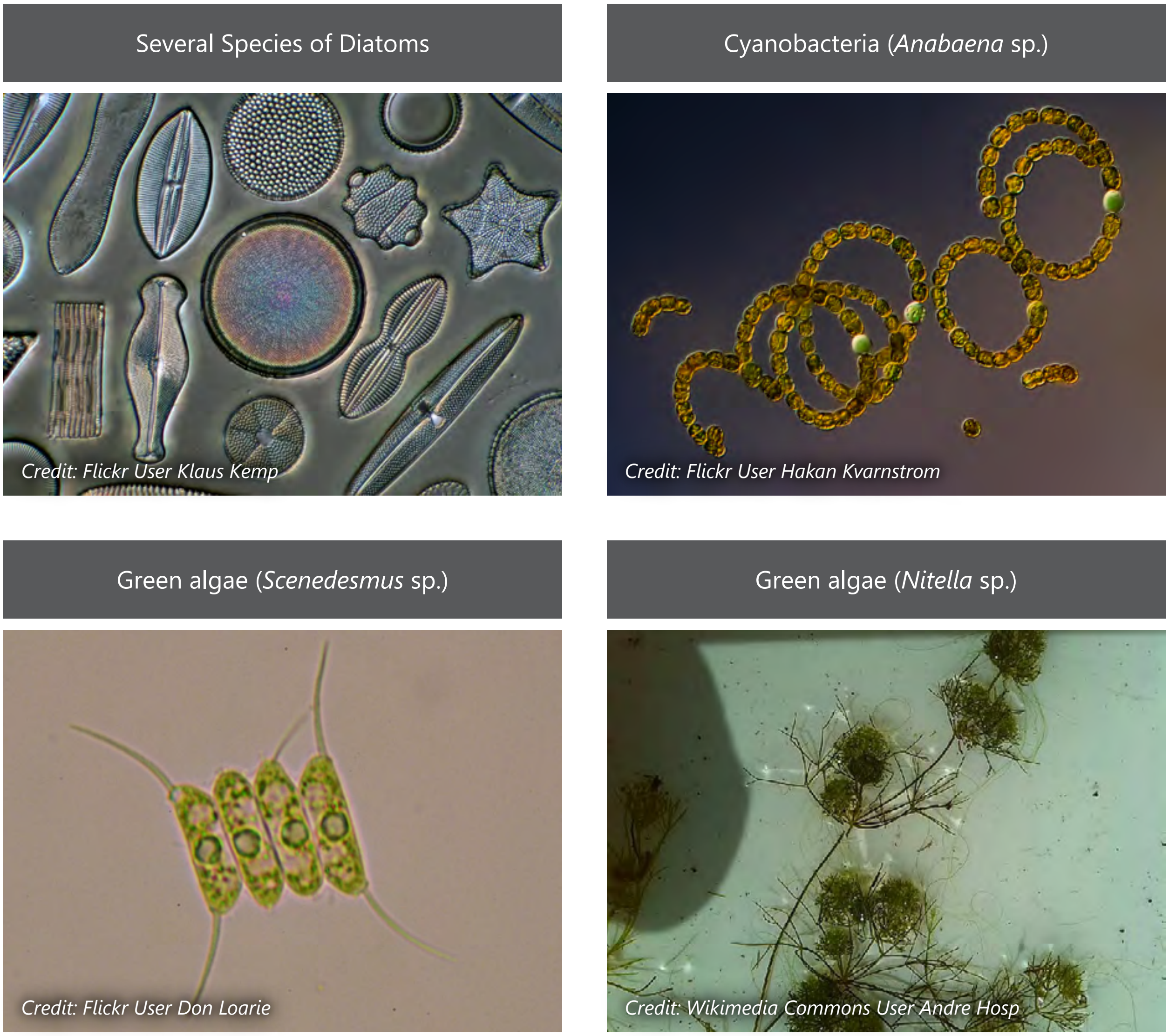
[243] *D.J. Steele, D.J. Franklin, and G.J. Underwood, "Protection of Cells from Salinity Stress by Extracellular Polymeric Substances in Diatom Biofilms,"* Biofouling*, 308:987-998, 2014.*

[244] *S.E. DeVilbiss, M.K. Steele, L.-A.H. Krometis, and B.D. Badgley, "Freshwater Salinization Increases Survival of* Escherichia coli *and Risk of Bacterial Impairment,"* Water Research, *191: 116812, 2021.*

[245] *A.F. Carlucci, and D. Pramer, "An Evaluation of Factors Affecting the Survival of* Escherichia *coli in Seawater. II. Salinity, pH, and Nutrients,"* Applied Microbiology, *8:247-250, 1960; I.C. Anderson, M. Rhodes, and H. Kator, "Sublethal Stress in* Escherichia coli*: A Function of Salinity,"* Applied and Environmental Microbiology, *38:1,147-1,152, 1979.*

[246] *DeVilbiss et al 2021,* op. cit.

Figure 3.2
Examples of Algae Found in Freshwater



Source: Flicker and Wikimedia Commons

Limited information is available on the impacts of chloride and chloride salts on freshwater algae. Detailed information on their salinity tolerance is lacking because only a few species in a few groups have been examined. There is a similar lack of detailed knowledge on the effects of chloride salts on algal physiology.

Phytoplankton and periphyton are commonly found in lake, pond, stream, river, and wetland environments. They serve as food sources to protozoa, zooplankton, macroinvertebrates, tadpoles, and fish. Most of the available information on the effects of chloride salts and salinity on algae comes from three groups: the blue-green algae or cyanobacteria, the diatoms or Bacillariophyta , and the green algae or Chlorophyta. The green algae include some macroalgae such as stoneworts in the genera *Nitella* and *Chara*.

Some studies have found that higher salinity reduces the concentration of planktonic algae in the water column.[247] Other studies have reported increases in phytoplankton concentrations with increasing salinity.[248] Increases in salinity were also found to reduce the photosynthetic efficiency of periphytic algae growing on rock.[249] This may be due to chloride ions inhibiting the activity of carbonic anhydrase, an enzyme that is important in preparing carbon dioxide for use in photosynthesis.[250] This inhibition may also account for the toxicity of chloride to some algal species.

Limited information is available on the effects of chloride on cyanobacteria. Higher salinity has been reported to favor the growth of some cyanobacteria species because they require sodium ions for growth.[251]

Concentrations of chloride and chloride salts can affect the presence and growth of diatoms. A paleolimnological study of 309 lakes in the northeastern U.S. characterized the optimal chloride concentrations for the presence of 235 common diatom species.[252] The study found that optimal chloride concentrations for diatoms ranged between 0.3 mg/l and 39 mg/l. Through the disappearance of diatom species with optima at low chloride concentrations and the appearance of species with optima at higher chloride concentrations in sediment cores, this study was able to document changes in chloride concentrations in many of the lakes examined. Another study characterized optimal chloride concentrations and levels of specific conductance for 191 species of periphytic diatoms in samples from 1,109 sites on rivers in the United States.[253] Optimum concentrations of chloride for periphytic diatoms ranged between 1.1 mg/l and 58.5 mg/l and optimum levels of specific conductance ranged between 40 μS/cm and 902 μS/cm. These optimal concentrations suggest that impacts to diatoms might occur at relatively low chloride concentrations.

Periphytic diatom species are important indicators of environmental stress. Because they are found in shallow areas near the shore or bank, periphytic diatoms are in the first areas to receive materials from anthropogenic stressors. Significant changes in the species of periphytic diatoms present have been reported with increases in chloride concentration in both lakes[254] and streams.[255] One study sampled diatom communities in 41 streams with chloride concentrations ranging from 5 mg/l to 502 mg/l.[256] It found a strong association between salinity and species composition of the diatom community. In addition, substantial

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[247] *J.C. Batterton and C. Baalen, "Growth Responses of Blue-green Algae to Sodium Chloride Concentration,"* Archives of Microbiology, *76:151-165, 1971; L.M. Kipriyanova, N.I. Yermolaeva, D.M. Bezmaternykh, S.Y. Dvurechenskaya, and E.Y. Mitrofanova, "Change in the Biota of Chany Lake Along a Salinity Gradient,"* Hydrobiologia*, 576:83-93, 2007; E. Coring and J. Bäthe, "Effects of Reduced Salt Concentration on Plant Communities in the River Werra (Germany),"* Limnologica*, 41:134-142, 2011.*

[248] *W.D. Hintz, B.M. Mattes, M.S. Schuler, D.K. Jones, A.B. Stoler, L. Lund, and R.A. Relyea, "Salinization Triggers a Trophic Cascade in Experimental Freshwater Communities with Varying Food-chain Length,"* Ecological Applications, *27:833-844, 2017.*

[249] *E.I.L. Silva and R.W. Davies, "The Effects of Simulated Irrigation Induced Changes in Salinity on the Metabolism of Lotic Biota."* Hydrobiologia*, 416:193-202, 1999.*

[250] *M.L. Dionisio-Sese and S. Miyachi, "The Effect of Sodium Chloride on Carbonic Anhydrase Activity in Marine Microalgae,"* Journal of Phycology, *28:619-624, 1992.*

[251] *M.B. Allen and D.I. Arnon, "Studies on Nitrogen Fixing Blue-green Algae. II. The Sodium Requirements of* Anabaena cylindrica*,"* Physiologia Plantarum*, 8:653-660, 1955.*

[252] *S.S. Dixit, J.P. Smol, R.M. Hughes, S.G. Paulsen, and G.B. Collins, "Assessing Water Quality Changes in Lakes of the Northeastern United States Using Sediment Diatoms,"* Canadian Journal of Fisheries and Aquatic Sciences, *56:131-152, 1999.*

[253] *M. Potapova and D.F. Charles, "Distribution of Benthic Diatoms in U.S. Rivers in Relation to Conductivity and Ionic Composition,"* Freshwater Biology, *48:1,311-1,328, 2003.*

[254] *M.J. MacDougall, A.M. Patterson, J.G. Winter, F.C. Jones, L.A. Knopf, and R.I. Hall, "Response of Periphytic Diatom Communities to Multiple Stressors Influencing Lakes in the Muskoka River Watershed, Ontario, Canada,"* Freshwater Science*, 36:77-89, 2017.*

[255] *E.R. Porter-Goff, P.C. Frost, and M.A. Xenopoulos, "Changes in Riverine Benthic Diatom Community Structure along a Chloride Gradient,"* Ecological Indicators*, 32:97-106, 2013.*

[256] Ibid.

changes occurred in the species making up diatom communities at a threshold chloride concentration of about 35 mg/l. Taxonomic changes also occurred as chloride concentrations increased above this threshold, but the changes were more gradual. Measures of diatom community diversity did not change with increasing chloride concentrations, suggesting that sensitive species dropped out of the community and were replaced by more tolerant species as chloride concentration rose.

Impacts of chloride to diatom species in other parts of the freshwater environment have also been reported. Shifts in the species composition of diatom assemblages were observed following salt pollution in the River Wipper in Germany.[257] Salinization has also been reported to reduce the density of diatom cells in freshwater biofilms.[258] Higher salinity has also been reported to result in changes to the external morphology of diatom cells.[259]

Differing effects of chloride have been reported for green algae. One study found that increased salinity favors the growth of some species in the genera *Chlorella, Ankistrodesmus, and Scenedesmus*.[260] In addition, laboratory experiments with two green algal species showed that growth was enhanced by increasing the concentration of sodium chloride over that which was found in the pond from which they were isolated.[261] Growth of *Chlorococcum humicola* was enhanced at chloride concentrations ranging between 182 and 2,914 mg/l. Similar enhancement was observed in *Scenedesmus bijugatus* at chloride concentrations ranging between 182 and 1,457 mg/l. In both species inhibition of growth occurred at a chloride concentration of 11,654 mg/l.

Other studies have found that increasing chloride concentrations caused adverse effects in some species of green algae. One study exposed *Scenedesmus obliquus* to sodium chloride at chloride concentrations ranging between 2,340 and 11,690 mg/l.[262] It found that the growth rate of the cells, their dry weight, their total protein content, and their cellular concentration of photosynthetic pigments all decreased with increasing sodium chloride concentration. Another study found that higher salt concentrations resulted in reduced abundance of filamentous algae.[263]

Few data were available on the effects of chloride on multicellular freshwater algae. One study found that increased chloride concentrations resulted in reduced biomass and chlorophyll-a content of the Charophyte alga *Nitella*.[264]

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[257] *H. Ziemann, L. Kies, and C.-J. Schulz, "Desalinization of Running Waters. III. Changes in the Structure of Diatom Assemblages Caused by a Decreasing Salt Load and Changing Ion Spectra in the River Wipper (Thuringia, Germany),"* Limnologica*, 31:257-280, 2001.*

[258] *S. Busse, R. Jahn, and C.-J. Schulz, "Desalinization of Running Waters. II. Benthic Diatom Communities: A Comparative Field Study on Responses to Decreasing Salinities,"* Limnologica*, 29:465-474, 1999.*

[259] *R. Trobajo, L. Rovira, D.G. Mann, and E.J. Cox, 'Effects of Salinity on Growth and Valve Morphology of Five Estuarine Diatoms,"* Phycological Research, *592:83-90, 2011.*

[260] *E. Kessler, "Physiological and Biochemical Contributions to the Taxonomy of the General* Ankistrodesmus *and* Scenedesums. *IV. Salt Tolerance and Thermophily,"* Archives for Microbiology, *119:13-16, 1977; E. Kessler, "Mass Culture of* Chlorella *Strains under Conditions of High Salinity, Acidity, and Temperature,* Archiv *für* Hydrobiologie, Supplement *60:80-86, 1980.*

[261] *R.C. Dash, P.K. Mohapatra, and R.C. Mohanty, "Salt Induced Changes in the Growth of* Chlorococcum humicola *and* Scenedesmus bijugatus *under Nutrient Limited Cultures,"* Bulletin of Environmental Contamination and Toxicology*, 54:695-702, 1995.*

[262] *A.A. Mohammet and A.A. Shafea, "Growth and Some Metabolic Activities of* Scenedesmus obliquus *under Different NaCl Concentrations,"* Biologia Plantarum*, 34:423-430, 1992.*

[263] *L. Lind, M.S. Schuler, W.D. Hintz, A.B. Stoler, D.K Jones, B.M. Mattes, and R.A. Relyea, "Salty Fertile Lakes: How Salinization and Eutrophication Alter the Structure of Freshwater Communities,"* Ecosphere*, 9:e02383, 2018.*

[264] Ibid.

Aquatic Plants (Macrophytes)

Aquatic plants, or macrophytes, include both mosses and vascular plants. These form an integral part of the aquatic food web, converting carbon dioxide and inorganic nutrients present in the water and sediments into organic compounds that are directly available as food for other aquatic organisms. In this process, known as photosynthesis, plants utilize energy from sunlight and release oxygen required by other aquatic life forms. Macrophytes provide food and habitat for fish and other aquatic organisms, produce oxygen, and may remove nutrients and pollutants from the water that could otherwise cause algal blooms or other problems. Examples of aquatic macrophytes are shown in Figure 3.3.

Aquatic plants are often described using the terms submerged, floating-leaf, free-floating, and emergent, depending on where the plant is found in the lake, stream, or wetland system. Emergent plants, such as bulrushes and cattails, are rooted in the substrate and have leaves that emerge above the water. They are commonly found in shallow areas such as along the shoreline areas of a lake. Submerged plants such as eelgrass (*Vallisneria americana*), are rooted in the bottom substrate and grow entirely under water. They can grow in deeper water than emergent plants but are restricted to depths in which light can penetrate. Floating-leaf plants, such as water lilies, are rooted in the substrate and generally have large, floating leaves. They are usually found in shallow water areas of a few feet in depth or less that contain loose bottom sediments. Free-floating plants, such as duckweed (*Lemna* spp.), have small leaves, are not rooted to the sediment, and are often blown around the waterbody by wind. All four macrophyte types play significant roles in aquatic systems.

Limited information is available on the impacts of chloride and chloride salts on freshwater aquatic plants. Detailed information on their salinity tolerance is lacking because few species have been examined.

<u>Chloride Tolerance of Aquatic Plants</u>

Most freshwater aquatic plant species cannot tolerate concentrations of dissolved salts greater than 10,000 mg/l. [265] Some freshwater macrophyte species die when chloride concentrations are between 1,000 mg/l and 2,000 mg/l[266] and a large proportion of them are sensitive to salinity that produces specific conductance in the range of 1,500 μS/cm to 3,000 μS/cm.[267] Woody aquatic plant species are often sensitive to salinity.[268] Young plants may also be particularly sensitive to the effects of chloride salts because of the role of water in plant growth and development.[269] The expansion of newly divided plant cells occurs through the cells taking up water and using the pressure from this water to increase cell size prior to synthesis of the final layers of the cell wall. Higher salt concentrations in the environment may interfere with this growth process.

The tolerance to chloride salts varies among aquatic plant species and by the type of salt and the duration and intensity of exposure to the salt.[270] For example, a field study found that almost all the endemic plant species were absent from the portion of an Indiana bog impacted by road salt when the concentration of chloride reached 1,215 mg/l.[271] Some macrophyte species disappeared at lower concentrations. For

[265] *P. Lacoul and B. Freedman, "Environmental Influences on Aquatic Plants in Freshwater Ecosystems,* Environmental Reviews, *14:89-136, 2006.*

[266] *B.T. Hart, P. Bailey, R. Edwards, K. Hortle, K. James, A. McMahon, C. Meredith, and K. Swadling "A Review of the Salt Sensitivity of the Australian Freshwater Biota,"* Hydrobiologia*, 210:105-144, 1991.*

[267] *K.R. James, B. Cant, and T. Ryan "Responses of Freshwater Biota to Rising Salinity Levels and Implications for Saline Water Management: A Review,"* Australian Journal of Botany, *51:703-713, 2003 and L.M. Kipriyanova, N.I. Yermolaeva, and D.M. Bezmaternykh, "Change in the Biota of Chany Lake Along a Salinity Gradient,"* Hydrobiologia, *576:83-93, 2007.*

[268] *W. Conner, K. McLeod, and J. McCarron, "Flooding and Salinity Effects on Growth and Survival of Four Common Forested Wetland Species,"* Wetlands Ecology and Management*, 5:99-109, 1997 and K.W. Krauss, J.L. Chambers, and D. Creech, "Selection for Salt Tolerance in Tidal Freshwater Swamp Species: Advances Using Baldcypress as a Model for Restoration," pages 385-410 in W.H. Conner, T.W. Doyle, and K.W. Krauss (editors),* Ecology of Tidal Freshwater Forested Wetlands of the Southeastern United States, *Springer, Dordrecht, The Netherlands, 2007.*

[269] *M. Rahman, U.A. Soomoro, M.Z. Haq, and S. Gul, "Effects of NaCl Salinity on Wheat (*Triticum aestivum *L.) Cultivars,"* World Journal of Agricultural Sciences*, 4:398-403, 2008.*

[270] *Lacoul and Freedman 2006,* op. cit.

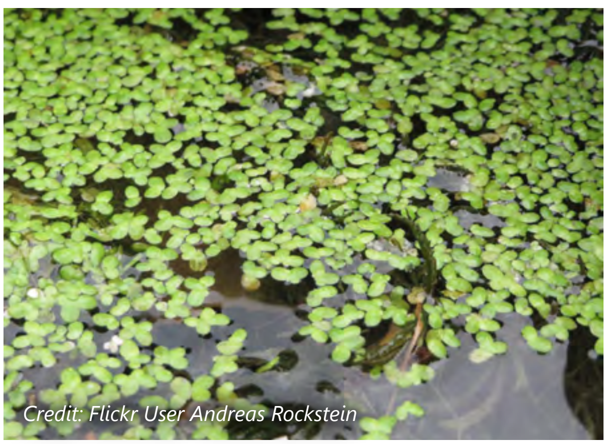
[271] *D.A. Wilcox, "The Effects of Deicing Salts on Vegetation in Pinhook Bog, Indiana,"* Canadian Journal of Botany, *64:865-874, 1986.*

Figure 3.3
Examples of Aquatic Macrophytes

Common Waterweed (*Elodea canadensis*)

Coontail (*Ceratophyllum demersum*)

Duckweed (*Lemna minor*)



Long-Leaf Pondweed (*Potamogeton nodosus*)

Source: Flicker and Wikimedia Commons

example, the peat moss *Sphagnum recurvum* was not seen in this wetland when chloride concentrations exceeded 500 mg/l.[272] Exotic species were less affected and many of the endemic species returned following a 50 percent reduction in the salt concentration.

Impacts of Chloride Salts on Aquatic Plants

High concentrations of salts can induce several types of sublethal effects in aquatic plants. Both submergent and emergent plants may experience these. Examples of these sublethal effects include reductions in height, length, or overall size; biomass; leaf size or proliferation; and flowering as well as displaying signs of injury such as leaf burn, wilting, and discoloration.[273] Sublethal effects of salinity are discussed in the following paragraphs.

[272] *D.A Wilcox, "The Effects of NaCl Deicing Salts on* Sphagnum recurvum *P. Beauv.,"* Environmental and Experimental Botany, *24:295-304, 1984.*

[273] *K. James and B. Hart, "Effect of Salinity of Four Freshwater Macrophytes,"* Marine and Freshwater Research, *44:769-777, 1993.*

Higher concentrations of chloride and other salts can lead to reductions in the growth of aquatic plants. These changes can be observed as reductions in size or reductions in biomass. For example, a laboratory study found that growth of the peat moss *Sphagnum recurvum* was reduced at chloride concentrations between 300 mg/l and 1,500 mg/l.[274] Based on the growth during exposure to other salts, chloride ions appear to be stronger inhibitors of growth to this moss than sodium ions. The moss also showed signs of injury from salts. As water evaporated from *Sphagnum* fronds, salt was deposited on the tips of the plant. This led to the death of the plant within three weeks, unless the salt was washed off.

Increases in chloride concentration have also been reported to decrease the biomass of aquatic plants. A laboratory study found that the wet weight of the duckweed *Lemna minor* decreased as the concentration of chloride increased.[275] This accompanied a decrease in the somatic growth rate of this plant. The surface area of leaves on the plants also decreased with increasing chloride concentration.

Similar effects on growth were observed in a study of pond weeds in the genus *Potamogeton*. The biomass of three *Potamogeton* species was lower when grown at a chloride concentration of 250 mg/l than in controls.[276] The somatic growth rates of these plants were also lower at a chloride concentration of 250 mg/l. The same study found no reduction of growth in the fan-leaved water crowfoot (*Rannunculus circinatus*) at the 250 mg/l level. This study also found that the number of leaves on individual *Potamogeton* plants and the surface areas of those leaves were reduced when exposed to the higher chloride concentration. This may be related to reduced expansion of leaf cells during growth and may result in reduced photosynthesis by the plants. This leaf impact was not observed in *R. circinatus*. The differences in the results between the *Potamogeton* species and *R. circinatus* may reflect differences in the sensitivities of these two genera to this concentration of chloride.

In vascular plants, salinization can lead to reduced carbon fixation through photosynthesis.[277] For example, photosynthetic production begins to decrease in common waterweed (*Elodea canadensis*) when chloride concentration rises to 100 mg/l.[278] Reduced photosynthesis can lead to reductions in plant growth, reproduction and viability. In part, reduction in photosynthesis may reflect the changes in the number and morphology of leaves that occur at higher concentrations of salts. It may also result from changes to the plant's photosynthetic apparatus. Decreases in plant concentrations of chlorophyll-a and other photosynthetic pigments with increasing salinity and sodium chloride concentration have been reported for *Lemna minor*.[279] Changes in cellular photosynthesis pigment content has also been reported in water thyme (*Hydrilla verticullata*), guppy grass (*Najas indica*), and rice field water nymph (*Najas gramenia*).[280]

Increases in the concentration of chloride and chloride salts can also reduce reproduction of aquatic plants which can happen in several ways. High concentrations of chloride can lead to reduced flower production in some aquatic plants. For example, the number of flowers produced by shining pondweed (*Potamogeton lucens*), redhead pondweed (*Potamogeton perfoliatus*), and long-leaf pondweed (*Potamogeton nodosus*) was lower in cultures with chloride concentration of 250 mg/l than in controls.[281] Exposure to saline conditions

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[274] *Wilcox 1984*, op. cit.

[275] *Ł. Sikorski, A.I. Piortrowicz-Cieślak, and B. Adomas, "Phytotoxicity of Sodium Chloride Towards Common Duckweed (*Lemna minor *L.) and Yellow Lupin (*Lupinus luteus *L.),"* Archives of Environmental Protection*, 39:117-128, 2013.*

[276] *F.W.B. van den Brink and G. van der Velde, "Growth and Morphology of Four Freshwater Macrophytes Under the Impact of the Raised Salinity Level of the Lower Rhine"* Aquatic Botany*, 45:285-297, 1993.*

[277] *W.E. Odum, "Comparative Ecology of Tidal Freshwater and Salt Marshes,"* Annual Review of Ecology and Systematics*, 19:147-176, 1988; Hart et al. 1991*, op. cit.*; and James et al. 2003,* op. cit.

[278] *H. Zimmerman-Timm, "Salinization in Inland Waters," pages 133-136 in: J. Lozan, H. Graßl, P. Hupfer, L. Menzel, and C. Schönwiese (editors),* Water Uses and Human Impacts on the Water Budget*, Verlag Wissenschaftliche Auswertungen/GEO, Hamburg, Germany, 2007.*

[279] *E.C. Keppeler, "Toxicity of Sodium Chloride and Methyl Parathion on the Macrophyte* Lemna minor *(Linnaeus, 1753) with Respect to Frond Number and Chlorophyll,"* Biotemas*, 22:27-33, 2009; J.A. Simmons, "Toxicity of Major Cations and Anions (Na^+, K^+ Ca^{2+}, Cl^-, and SO_4^{2-}) to a Macrophyte and an Alga,"* Environmental Toxicology and Chemistry*, 31:1,370-1,374, 2012.*

[280] *N.P. Rout and B.P Shaw, "Salt Tolerance in Aquatic Macrophytes: Ionic Relation and Interaction,"* Biologia Plantarum*, 44:95-99, 2001.*

[281] *van den Brink and van der Velde 1993,* op. cit.

can also reduce seed germination of aquatic plants.[282] Sodium chloride concentrations of 3,000 mg/l were reported to reduce seed germination in sago pondweed (*Potamogeton pectinatus*).[283] Similarly, a three-month experiment testing the emergence of plants from a wetland seed bank found that constant exposure to salinity of 1,000 mg/l and 5,000 mg/l reduced both the abundance and diversity of seeds germinating.[284] Reduction in germination was not observed when seeds were exposed to a 14-day pulse of saline water followed by freshwater. This suggests that some seeds may be able to tolerate shorter exposures to chloride salts. Finally, vegetative reproduction in aquatic plants can be favored over sexual reproduction in salinized environments.[285] This can reduce a waterbody's genetic diversity in species, potentially making them more vulnerable to other stressors.

<u>Mechanisms Underlying Chloride Salt Impacts on Aquatic Plants</u>

Several mechanisms likely underlie the effects of chlorides and chloride salts on aquatic plants. First, excessive concentrations of sodium chloride can impede the ability of plants to absorb water.[286] Unlike animal cells, plant cells have a rigid cell wall and a large central vacuole. Under normal conditions, water flows into the cell and into the vacuole, causing the cell membrane to press against the cell wall. This is referred to as turgor. Higher than normal concentrations of salts in the environment can cause the cell to lose water, reducing turgor. With enough water loss, the cell membrane may pull away from the cell wall. Non-turgid conditions adversely affect the functioning of the plant and if they persist, they can eventually lead to death of the plant.

The effects of chloride-associated cations on energy metabolism may also play a role in the impacts of chloride salts on aquatic plants. During energy metabolism, positively charged ions are passed across internal membranes within cells. Excessive sodium ions in the environment can lead to changes in a plant's internal balance between sodium ions and potassium ions. This could require that the plant expend energy to compensate for this change, leading to slower growth or chlorophyll production.[287] In any case, the physiological mechanisms that mitigate salt stress in plants come at a cost of reduced growth, reproduction, and competitive ability.[288]

Zooplankton

Zooplankton are free-floating animals that can be found in the water columns of lakes, wetlands, and streams. They are typically small, with lengths less than 2 millimeters. Zooplankters are consumers of phytoplankton, bacteria, and protists and key grazers on algal populations.[289] Zooplankton, in turn, are significant prey for invertebrate and fish predators.[290] As such, they provide a critical link in aquatic food webs, passing production from primary producers to higher trophic levels. Most zooplankton in freshwater systems are members of four groups of organisms: Cladocera, copepods, ostracods, and rotifers. The first three groups are members of the crustacea, and the fourth group is a separate phylum of invertebrates. Examples of zooplankton are shown in Figure 3.4

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[282] *D.L. Nielsen, M.A. Brock, K. Crosslé, K. Harris, M. Healy, and M. Jarosinski, "The Effects of Salinity on Aquatic Plant Germination and Zooplankton Hatching from Two Wetland Sediments,"* Freshwater Biology, *48:2,214-2,223, 2003.*

[283] *J.W. Teeter,* The Influence of Sodium Chloride on the Growth and Reproduction of the Sago Pondweed (*Potamogeton pecinatus* L.), *Master's Thesis, Utah State University, Logan, Utah, 1963.*

[284] *D.L. Nielsen, M.A. Brock, R. Petrie, and K. Crosslé, "The Impact of Salinity Pulses on the Emergence of Plant and Zooplankton from Wetland Seed and Egg Banks,"* Freshwater Biology, *52:784-795, 2007.*

[285] *R.W. Robinson, E.A. James, and P.I. Boon, "Population Structure in the Clonal, Woody Wetland Plant* Melaleuca ericifolia *(Myrtaceae): An Analysis Using Historical Aerial Photographs and Molecular Techniques,"* Australian Journal of Botany, *60:9-19, 2012.*

[286] *J.K. Zhu, "Plant Salt Tolerance,"* Trends in Plant Science, *6:66-71, 2001.*

[287] *Simmons 2012,* op. cit.

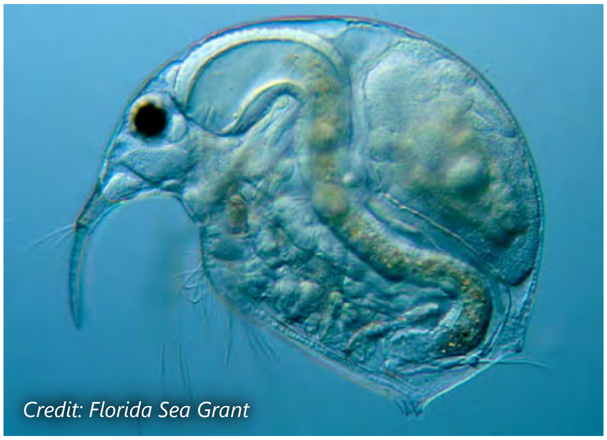
[288] *R. Munns, and M. Tester, "Mechanisms of Salinity Tolerance,"* Annual Review of Plant Physiology, *59:651-668, 2008.*

[289] *W. Lampert, W. Fleckner, H. Rai, and B.E. Taylor, "Phytoplankton Control by Grazing Zooplankton: A Study on the Spring Clear-water Phase,"* Limnology and Oceanography, *31:478-490, 1986.*

[290] *P. Larsson and S. Dodson, "Invited Review—Chemical Communication in Planktonic Animals,"* Archive für Hydrobiologie, *129:129-155, 1993.*

Figure 3.4
Examples of Freshwater Zooplankton

Cladoceran (*Bosmina* sp.)



Copepod (*Cyclopse* sp.)

Ostracod (unknown species)

Rotifer (*Brachionus calyciflorus*)

Source: Florida Sea Grant, Flickr, and Wikimedia Commons

Among zooplankton, the impacts of chloride and chloride salts have been studied the most in the Cladocera, and especially in water fleas of the family Daphniidae. Many studies have focused on *Ceriodaphnia dubia* and species in the genus *Daphnia* because they are readily cultured in laboratory settings and are commonly used in toxicology studies. Less information is available on impacts of chloride and chloride salts on predatory Cladocera, copepods, rotifers, and ostracods.[291]

Impacts of Chloride Salts on Zooplankton Abundance

High salinities and high concentrations of chloride salts are associated with lower abundance of zooplankton. For example, a field survey of 14 waterbodies with salinities ranging from 157 mg/l to 31,774 mg/l found that the densities and species richness of rotifers decreased with increasing salinity.[292] Reductions in zooplankton abundance with increasing chloride concentrations have been observed in mesocosm

[291] *W.D. Hintz and R.A. Relyea, "A Review of the Species, Community and Ecosystem Impacts of Road Salt Salinization in Freshwaters,"* Freshwater Biology, *64:1,081-1,097, 2019.*

[292] *I. Bielanska-Grajner and A. Cudak, "Effects of Salinity on Species Diversity of Rotifers in Anthropogenic Waterbodies,"* Polish Journal of Environmental Studies, *23:27-34, 2014.*

experiments in which communities have been exposed to different concentrations of chloride. Densities of cladocerans, copepods, and rotifers decreased with increasing concentrations of chloride in one experiment in which chloride concentrations ranged between 120 mg/l and 1,500 mg/l.[293] The impacts of chloride on zooplankton abundance differ among groups. Another mesocosm study found 85 percent reductions in the density of adult copepods and 94 percent reductions in the density of cladocerans relative to controls at a chloride concentration of 645 mg/l.[294] This experiment did not detect an effect of chloride on the abundance of rotifers, ostracods, or juvenile copepods.

The diverse chloride response of zooplankton groups may reflect differences in the biology of the groups, but also may reflect differences among individual species. Another study that exposed rotifer species to concentrations of sodium chloride ranging between 0 mg/l and 4,500 mg/l (chloride concentrations of 0 mg/l to 2,730 mg/l) found that rotifer abundance decreased with increasing sodium chloride concentration; however, the chloride concentration at which effects became apparent differed among species.[295] Reductions in the densities of populations of the species *Anuraeopsis fissa*, *Brachionus calyciflorus,* and *Brachionus havanaensis* were detected at sodium chloride concentrations above 1,500 mg/l or chloride concentrations of about 910 mg/l, while reductions in the species *Brachionus patulus,* and *Brachionus rubens* were detected at sodium chloride concentrations above 3,000 mg/l or chloride concentrations of 1820 mg/l. Greater reductions typically occur at higher chloride concentrations. For example, the abundance of *Daphnia pulex* in a mesocosm study decreased by 40 percent relative to controls at chloride concentration of 860 mg/l.[296] The decrease relative to controls in a treatment with chloride concentration of 1,300 mg/l was about 79 percent. The reductions in zooplankton abundance are partially due to the impacts of acute toxicity that were discussed earlier in this chapter, but sublethal factors may also play a major role.

Impacts of Chloride Salts on Zooplankton Population Growth

Population growth rates of three *Daphnia* species have been reported to decrease with higher concentrations of sodium chloride.[297] In addition, the longevity of zooplankton is also affected by chloride. A life table analysis showed that the average lifespan and life expectancy at birth in *Daphnia magna* decreased with increasing concentration of sodium chloride.[298] Similar reductions in longevity were observed in the water flea *Pseudosida ramosa* when it was exposed to either sodium chloride or potassium chloride.[299]

The lower population growth rates reflect the fact that individual zooplankters may grow more slowly under higher salinity and higher concentrations of chloride. One study measured the body size of *Daphnia carinata* grown in chloride concentrations between 100 mg/l and 1,500 mg/l.[300] The body lengths attained by these water fleas decreased with increasing chloride concentrations. This indicates that the water fleas experienced reduced somatic growth rates with higher chloride concentrations. Similarly, the mean length,

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[293] *D.A. Greco, S.E. Arnott, I.B. Fournier, and B.S. Schamp, "Effect of Chloride and Nutrients on Freshwater Plankton Communities,"* Limnology and Oceanography Letters, *doi: 10.1002/lol2.10202, 2022.*

[294] *R.J. van Meter, C.M. Swan, J. Lepis, and J.W. Snodgrass, "Road Salt Stress Induces Novel Food Web Structure and Interactions,"* Wetlands*, 31:843-851, 2011.*

[295] *S.S.S. Sarma, S. Nandina, J. Morales-Ventura, I. Delgado-Martínez, and L. González-Valverde, "Effects of NaCl Salinity on the Population Dynamics of Freshwater Zooplankton (Rotifers and Cladocerans),"* Aquatic Ecology, *40:349-360, 2006.*

[296] *W.D. Hintz and R.A. Relyea, "A Salty Landscape of Fear: Responses of Fish and Zooplankton to Freshwater Salinization and Predatory Stress,"* Oecologia*, 185:147-156, 2017.*

[297] *A.M.M. Gonçalves, B.B. Castro, M.A. Pardal, and F. Gonçalves, "Salinity Effects on Survival and Life History of Two Freshwater Cladocerans (*Daphnia magna and Daphnia longispina*),"* Annales de Limnologie—International Journal of Limnology, *43:13-20, 2007; G. Bezrici, S.B. Akkas K. Rinke, F. Yildirim, Z. Kalaylioglu, F. Severcam, and M. Beklioglu, "Impacts of Salinity and Fish-exuded Kairomone on the Survival and Macromolecular Profile of* Daphnia pulex," Ecotoxicology*, 21:601-614, 2012.*

[298] *F. Martínez-Jerónimo and L. Martínez-Jerónimo, "Chronic Effects of NaCl Salinity on a Freshwater Strain of* Daphnia magna *Straus (Crustacea: Cladocera): A Demographic Study,"* Ecotoxicology and Environmental Safety, *67:411-416, 2007.*

[299] *E.C. Freitas and O. Rocha, "Effects of Sodium and Potassium on Life History of the Freshwater Cladoceran* Pseudosida ramosa," Journal of the Brazilian Society of Ecotoxicology, *7:85-91, 2012.*

[300] *Hall and Burns 2002,* op. cit.

wet weight, and dry weight attained by *Daphnia magna* were lower with increasing sodium chloride concentration.[301] The ratio of body width to body length in *Daphnia pulex* decreased with rising sodium chloride concentration, indicating slower growth.[302] This was accompanied by a decrease in lipid content in the organisms, suggesting that they had lower energy reserves. The maximum body size attained by *Pseudosida ramosa* was also shorter when it was cultured at higher concentrations of sodium.[303] Finally, lower somatic growth rates with increasing salinity[304] and sodium chloride concentration[305] have been reported in *Daphnia pulicaria*.

The reduction in somatic growth rates associated with higher chloride concentrations may be due to salinity or chloride acting to inhibit feeding by zooplankton. One study found that feeding rates in six clonal lineages of *Daphnia longispina* decreased as salinity rose.[306] Similarly, one out of five experimental populations of *Daphnia dentifera* collected from different lakes showed reductions in feeding when exposed to sodium chloride concentrations of 600 mg/l.[307] Reduced feeding rates result in the organism obtaining fewer nutrients and less matter to fuel growth, resulting in slower somatic growth rates and ultimately slower population growth rates.

Impacts of Chloride Salts on Zooplankton Mobility

Exposure to chloride salts can also affect the ability of zooplankton to move. For example, swimming velocity in many zooplankton species is dependent on size. In experiments that controlled for the effects of size, exposure of *Daphnia magna* to salinity decreased their swimming velocity.[308] Related experiments showed that this effect could not be accounted for by reduced food intake. The swimming velocity gradually returned to normal under saline conditions, but this was accompanied by considerable mortality in the test animals. The authors concluded that increased salinity temporarily impaired *Daphnia* physiology. This temporary reduction in swimming velocity could lead to greater exposure of daphnids to predators.

Exposure to chloride salts can also affect another type of zooplankton movement. Many zooplankton show phototactic responses, moving away from light. Exposure of *Daphnia magna* to sublethal concentrations of sodium chloride led to disruption of phototactic responses in their offspring.[309] This can disrupt the typical vertical migration in zooplankton populations.

Many freshwater zooplankton species migrate vertically through the water column on a daily basis. Typically, they move downward into darker bottom waters at dawn and upward into surface layers at dusk.[310] This is likely a means of avoiding predation by visually feeding predators such as many fish, with dark bottom waters serving as a refuge during the day when feeding rates of visual predators are higher.[311] Disruption of this response to light by sodium chloride can lead to greater exposure of zooplankton to predators.

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[301] *M.M. El-Deeb Ghazy, M.M Habashy, F.I. Kossa, and E.Y. Mohammady, "Effects of Salinity on Survival, Growth and Reproduction of the Water Flea,* Daphnia magna," Nature and Science, *7:28-42, 2009.*

[302] *Bezrici et al. 2012,* op. cit.

[303] *Freitas and Rocha 2012,* op. cit.

[304] *C. Venâncio, R. Ribero, A.M.V.M. Soares, and I. Lopes, "Multigenerational Effects of Salinity, in Six Clonal Lineages of* Daphnia Longispina," Science of the Total Environment, *519-620:194-202, 2018.*

[305] *Gonçalves et al. 2007,* op. cit.

[306] *C. Venâncio et al. 2018,* op. cit.

[307] *C.L. Searle, C.L. Shaw. K.K. Hunsberger, M. Prado, and M.A. Duffy, "Salinization Decreases Population Densities of the Freshwater Crustacean* Daphnia dentifera," Hydrobiologia, *770:165-172, 2016.*

[308] *M Baillieul, B. DeWachter, and R. Blust, "Effect of Salinity on the Swimming Velocity of the Water Flea* Daphnia magna," Physiological Zoology, *71:703-707, 1998.*

[309] *M.A. Kolkmeier and B.W. Brooks, "Sublethal Silver and NaCl Toxicity in* Daphnia magna*: A Comparative Study of Standardized Chronic Endpoints and Progeny Phototaxis,"* Ecotoxicology, *22:693-706, 2013.*

[310] *H.-B. Stitch and W. Lampert, "Predator Evasion as an Explanation of Diurnal Vertical Migration by Zooplankton,"* Nature, *293:396-398, 1981; E.V. Van Gool and J. Ringelberg, "Quantitative Effects of Fish Kairomones and Successive Light Stimuli on Downward Swimming Responses of* Daphnia," Aquatic Ecology, *291:291-296, 1998.*

[311] *W. Lampert, "The Adaptive Significance of Diel Vertical Migration,"* Functional Ecology, *3:21-27, 1989.*

Impacts of Chloride Salts on Zooplankton Reproduction

Exposure to chloride and chloride salts can also reduce zooplankton reproduction. Several studies found lower reproductive output by the water flea *Ceriodaphnia dubia* begins to be observed at chloride concentrations in the range of about 150 mg/l to 520 mg/l and 50 percent reductions in reproductive output were seen at chloride concentrations in the range of about 350 mg/l to 965 mg/l.[312] Similar reductions in reproductive output have been reported in *Daphnia ambigua*,[313] *Daphnia magna*,[314] and the rotifer *Brachionus calyciflorus*.[315]

Chloride salts and salinity affect several aspects of zooplankton reproduction. First, exposure to chloride salts can increase the age at which reproduction first occurs. For example, exposure to potassium chloride increased the number of days needed for *Pseudosida ramosa* to reach maturity from 8.75 to 11.2.[316] Exposure to sodium chloride concentrations between 1,670 mg/l and 2,660 mg/l increased the time to first reproduction in *Daphnia magna* from seven days in controls to nine days in all treatments with added salt.[317] Increases in the age at first reproduction with increasing salinity or sodium chloride concentration have also been reported in *Daphnia longispina*[318] and the copepod *Gladioferens imparipes*.[319]

Second, exposure to chloride salts can reduce the size of reproductive broods. Many zooplankton, including most cladocerans and copepods, produce offspring in clutches or broods of a few to several eggs. Decreases in the average number of eggs produced per brood with increasing concentration of sodium chloride has been reported in *Daphnia longispina*[320] and *Daphnia pulex*.[321] In addition, increases in the time between production of broods and decreases in the total number of broods produced with higher sodium chloride concentrations have been observed in *Daphnia magna*.[322]

Third, exposure to chloride salts can reduce the total number of offspring produced per female zooplankter. One study that exposed *Ceriodaphnia dubia* and *Daphnia ambigua* to concentrations of sodium chloride ranging between 210 mg/l and 2,200 mg/l found that the total number of offspring produced over a female's lifetime was lowered with increasing chloride concentration.[323] A similar effect occurred when *Daphnia longispina* and *Daphnia magna* were exposed to sodium chloride.[324] Reductions in total lifetime reproductive output have also been reported for zooplankton exposed to potassium chloride. In one study, *Daphnia magna* exposed to a potassium chloride concentration of 8 mg/l produced an average of 74 offspring per female, while *Daphnia magna* exposed to concentration of 24 mg/l produced an average of 49 offspring per female.[325]

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[312] *M.A. Aragão and E.V. Pereira, "Sensitivity of* Ceriodaphnia dubia *of Different Ages to Sodium Chloride,"* Bulletin of Environmental Contamination and Toxicology," *70:1,247-1,250, 2003; S.H. Harmon, W.L. Specht, and G.T. Chandler, "A Comparison of the Daphnids* Ceriodaphnia dubia *and* Daphnia ambigua *for Their Utilization in Routine Toxicity Testing in the Southeastern United States,"* Archives of Environmental Contamination and Toxicology," *45:79-85, 2003; Elphick et al. 2011,* op. cit.

[313] *Harmon et al. 2003,* op. cit.

[314] *Elphick et al. 2011,* op. cit.

[315] Ibid.

[316] *Freitas and Rocha 2012,* op. cit.

[317] *El-Deeb Ghazy et al. 2009,* op. cit.

[318] *Gonçalves et al. 2007,* op. cit.

[319] *M. Grzesiuk and A. Mikulski, "The Effect of Salinity on Freshwater Crustaceans,"* Polish Journal of Ecology, *54:669-674, 2006.*

[320] *Gonçalves et al. 2007,* op. cit.

[321] *Bezrici et al. 2012,* op. cit.

[322] *Martínez-Jerónimo and Martínez-Jerónimo 2007,* op. cit.

[323] *Harmon et al. 2003,* op. cit.

[324] *Gonçalves et al. 2007,* op. cit.; *Martínez-Jerónimo and Martínez-Jerónimo 2007,* op. cit.

[325] *G.A. Leblanc and D.C. Suprenant, "The Influence of Mineral Salts on Fecundity of the Water Flea* Daphnia magna *and the Implication on Toxicity Testing of Industrial Wastewater,"* Hydrobiologia, *108:25-31, 1984.*

Impacts of Chloride Salts on Zooplankton Resting Eggs

Many zooplankton species produce two types of eggs. Their normal mode of reproduction is through subintaneous eggs that hatch within a few days of being developed. In addition to this, most cladoceran species and many species of copepods and rotifers produce resting eggs. These eggs are an adaptation that allows the species to weather unfavorable conditions. They are resistant to harsh environmental conditions and capable of extended periods of dormancy. Once formed, resting eggs sink to the substrate. Maximum concentrations of resting eggs in the substrate have been reported to range from 1,000 to 1,000,000 resting eggs per square meter. Hatching of resting eggs often serves to reestablish populations within a waterbody after they disappear due to reduced food levels, predation, or unfavorable environmental conditions.[326]

Studies have found that exposure to salinity and chloride salts can inhibit hatching of zooplankton resting eggs. One study collected three species of Great Lakes zooplankton, the water fleas *Bosmina liederi* and *Daphnia longiremis* and the rotifer *Brachionus calyciflorus*, from ballast sediments in ships and exposed them to several levels of salinity.[327] It found that the proportion of hatched eggs decreased with increasing salinity. At most, only 10 percent of the eggs that were exposed to elevated salinity hatched. In addition, the development of embryos in *Bosmina* and *Daphnia* eggs terminated at salinities equal to or greater than 8,000 mg/l. No hatching was seen at salinities higher than 8,000 mg/l, although some eggs that were exposed to this salinity hatched when placed into freshwater following exposure.

A second study exposed a mixture of resting eggs from different zooplankton species to levels of constant salinity ranging between 1,000 mg/l and 5,000 mg/l for a three-month period.[328] The abundance and diversity of zooplankton that hatched decreased with increasing salinity. Reduction in hatching was not observed when resting eggs were exposed to a 14-day pulse of saline water followed by freshwater. This suggests that some resting eggs may be able to tolerate exposure to chloride salts for a relatively short period of time.

Inhibition of resting egg hatching with increased salinity and concentrations of chloride salts may act as an additional stressor on zooplankton populations. This could reduce the likelihood of populations in salinized waterbodies reestablishing after experiencing other environmental stresses.

Factors that May Mitigate Zooplankton Sensitivity to Chloride Salts

In some instances, sensitivity of zooplankton to chloride and chloride salts may potentially be mitigated by other characteristics of the aquatic environment. For example, if food availability can modify sensitivity to higher chloride concentrations, zooplankton in environments with higher concentrations of food might be more tolerant of chloride.[329] An example of such an environment might be a eutrophic lake, although mitigation may also depend on the quality of the food. An indication that such mitigation can occur was found in a 14-day experiment that exposed a uniclonal hybrid of *Daphnia pulex* and *Daphnia pulicaria* to sodium chloride and calcium chloride.[330] At any given chloride concentration, zooplankton survival, brood size, egg production, and growth rate increased and age at first reproduction decreased with increasing food concentration. This suggests that food availability may mitigate some impacts of chloride in at least some zooplankton species.

Reduced impacts of chloride and chloride salts on zooplankton with greater food availability suggests that some impacts are related to energy demands placed upon the organism by higher salt concentrations. Regulating internal salt concentration in a salinizing freshwater environment requires that zooplankters increase their production of osmoprotectant compounds and cellular ion transporters.[331] This is energetically

[326] *N.G. Hairston, Jr., "Zooplankton Egg Banks as Biotic Reservoirs in Changing Environments,"* Limnology and Oceanography, *41:1,087-1,092, 1996.*

[327] *S.A. Bailey, I.C. Duggan, C.D.A. van Overdijk, T.H. Johengen, D.F. Reid, and H.J. MacIsaac, "Salinity Tolerance of Diapausing Eggs of Freshwater Zooplankton,"* Freshwater Biology, *49:286-295, 2004.*

[328] *Nielsen et al. 2007,* op. cit.

[329] *Greco et al. 2022,* op. cit.

[330] *Brown and Yan 2015,* op. cit.

[331] *L.C. Latta, L.J. Weider, J.K. Colbourne, and M.E. Pfrender, "The Evolution of Salinity Tolerance in* Daphnia*: A Functional Genomics Approach,"* Ecology Letters*, 15:794-802, 2012.*

costly and requires the use of resources that would otherwise be allocated to somatic growth and reproduction. This idea is supported by the previously mentioned finding that *Daphnia pulex* exposed to sodium chloride had lower energy reserves than those that were not exposed.

The presence of other ions in the water also affects the impact of chloride on zooplankton. For example, one study found that less severe reductions in reproduction in *Ceriodaphnia dubia* occur in water with greater hardness or alkalinity.[332] This suggest that chloride may impair osmoregulatory functions and/or acid base balance within the organism. It should be noted that this potential mechanism and the one discussed in the previous paragraph are not mutually exclusive.

Macroinvertebrates

Freshwater aquatic macroinvertebrates are animals without backbones that are large enough to be seen without a microscope. They are typically larger than one or two millimeters. Macroinvertebrates consist of several groups of animals, each with their own biological characteristics. Macroinvertebrates include bivalves such as mussels and clams; gastropods such as snails; annelids such as worms and leeches; crustaceans such as crayfish, amphipods, and isopods; and insects. Members of most of these groups spend their entire life cycle within water; however, only juvenile stages of many aquatic insect species are found in water. The adults in many aquatic insect species are terrestrial. Macroinvertebrates are important consumers in aquatic food webs. Many species process organic matter, breaking down large organic material such as leaves into smaller pieces. Others feed on small organic particles in the water column or sediment. Still others graze on algae and fungi that grow on the surfaces of rocks or aquatic plants. Macroinvertebrates in turn are significant prey for larger organisms such as fish, amphibians, birds, and mammals. Some examples of macroinvertebrates are shown in Figure 3.5.

Freshwater Macroinvertebrate Sensitivity to Chloride and Salinity

Some general features of the biology of many freshwater aquatic macroinvertebrates can make them sensitive to impacts from chloride salts and salinity. As freshwater organisms, they are adapted to an environment in which the salt concentration is lower than that of their internal fluids. Normally, the main problem that they face relative to salt concentration is keeping enough ions in their bodies.[333] Macroinvertebrate physiology is adapted to address this problem and not the opposite problem of keeping ions out. This can be an issue because they typically maintain the osmotic balance of their internal fluids within a narrow range. There are limits relative to external salt concentrations over which macroinvertebrates can do this. Outside of these limits, their ability to regulate osmotic pressure, or the tendency of water to flow into their bodies, breaks down.[334] In particular, they are generally incapable of maintaining body solute concentrations below that of the water in which they live. As the salinity of the environment increases, macroinvertebrates tend to take up more ions and lose water from cells until the cells can no longer function properly.[335] This can disrupt their metabolism and if the disruption is severe enough or prolonged, it can lead to organism death.

Freshwater organisms have two broad strategies for dealing with the osmotic challenges created by increased salinity.[336] First, they can adjust their intracellular osmotic pressure to meet that of the environment by synthesizing compatible solutes, such as amino acids and proteins. Some macroinvertebrates, such as salt marsh mosquitoes which inhabit brackish water environments, are capable of this, but many others lack this ability.[337] Second, they can maintain the volume of their body fluids and osmotic pressure through changes

[332] *P.J. Lasier and I.R. Hardin, "Observed and Predicted Reproduction of* Ceriodaphnia dubia *Exposed to Chloride, Sulfate, and Bicarbonate,"* Environmental Toxicology and Chemistry*, 29:347-358, 2010.*

[333] *A. Tiwari and J.W. Rachlin, "A Review of Road Salt Ecological Impacts,"* Northeaster Naturalist*, 25:123-142, 2018.*

[334] *B.J. Kefford, D. Nugegoda, L. Zalizniak, E.J. Fields, and K.L. Hassell, "The Salinity Tolerance of Freshwater Macroinvertebrate Eggs and Hatchlings in Comparison to Their Older Life-Stages: A Diversity of Responses,"* Aquatic Ecology*, 41:335-348, 2007.*

[335] *B.T. Hart, P. Bailey, R. Edwards, K. Hortle, K. James, A. McMahon, C. Meredith, and K. Swadling, "A Review of the Salt Sensitivity of Australian Freshwater Biota,"* Hydrobiologia*, 210:105-144, 1991.*

[336] *J. Velasco, C. Gutiérrez-Cánovas, M. Botella-Cruz, D. Sánchez-Fernández, P. Arribas, J.A. Carbonell, A. Millán, and S. Pallarés, "Effects of Salinity Changes on Aquatic Organisms in a Multiple Stressor Context,"* Philosophical Transactions of the Royal Society Series B*, 374:20180011, 2018.*

[337] *M.A Chadwick, H. Hunter, J.W. Feminella, and R.P Henry, "Salt and Water Balance in* Hexagenia limbate *(Ephemeroptera: Ephemeridae) When Exposed to Brackish Water,* The Florida Entomologist*, 85:650-651, 2002.*

Figure 3.5
Examples of Aquatic Macroinvertebrates

Fingernail Clam (*Musculium transversum*)

Credit: Flickr User Roger Boyd

Mayfly Larva (*Isonychia* sp.)

Credit: Flickr User Bob Henricks

Isopod (*Lirceus* sp.)

Credit: Flickr User Andrew Hoffman

Mosquito Larva (*Aedes aegypti*)

Credit: Flickr User Cesar Favacho

Backswimmer (*Notonecta glauca*)

Credit: Flickr User Andrew Hoffman

Eastern Elliptio Mussel (*Elliptio complanata*)

Credit: U.S. Fish and Wildlife Service

Source: Flickr and U.S. Fish and Wildlife Service in permeability of cell membranes and ion transport within different tissues.[338] This involves active transport of salt ions. For example, some aquatic insects, especially among mayflies, stoneflies, and caddisflies, have chloride cells that can transport chloride and sodium ions through active transport; however, in insects these cells only enable them to bring the ions into their bodies. They do not enable the insects to excrete them.

There are two consequences to either of these strategies to regulate chloride intake. First, they are better at enabling the organisms to tolerate conditions in which the salinity of the environment is lower than their internal salt concentration. For example, laboratory studies show that mayflies, stoneflies, and caddisflies better tolerate conditions in which environmental salinity is lower than their internal salt concentrations.[339] Second, using either of these strategies requires expenditure of energy by the organism. This reduces the energy that is available for growth and reproduction and can lead to a variety of impacts on the organism which will be discussed later in this section.

The specific habitats in which many macroinvertebrates live is a second aspect of their biology which can make them sensitive to impacts from chloride salts. Many macroinvertebrates live on or within the bed substrates of streams, lakes, or wetlands. As described in Chapter 2 of this report, introduction of chloride salts into a waterbody can result in the formation of a dense layer of water containing a relatively high concentration of chloride immediately above the bottom of the waterbody. This can expose organisms living on and in the substrate to higher chloride concentrations than would be experienced by organisms living higher in the water column.[340] Freshwater mussels are a good example of macroinvertebrates that may experience higher exposure to chloride salts due to their living in benthic habitat. In addition, since juvenile mussels in many species remain burrowed during early life stages, they may also experience higher exposure to chloride if groundwater or water in the hyporheic zone beneath the bed surface is contaminated with salt.[341]

Macroinvertebrates differ in their sensitivity to chloride salts and salinity. Mayflies and stoneflies in the insect orders Ephemeroptera and Plecoptera and air-breathing (pulmonate) snails are particularly sensitive to salinity.[342] For example, in field settings species richness in mayfly, stonefly, and caddisfly taxa decreases with increasing salinity.[343] Similarly, the number of genera of mayflies present at sites was found to decrease with increasing chloride concentration.[344] On the other hand, larval beetles, dragonflies, and damselflies in the insect orders Coleoptera and Odonata are more tolerant of salinity. This is also the case of some crustaceans and some true flies in the insect order Diptera, including some mosquito and biting midge species.[345]

Tolerance of aquatic macroinvertebrate groups to chloride salts and salinity may be based upon specific biological or life history traits. Field studies conducted in rivers in Germany and France that had low salinity upstream and high salinity downstream due to point source discharges showed clear differences in the traits that were associated with different levels of specific conductance. These differences accounted for about 30 percent of the variation in the data.[346] Macroinvertebrates found in high specific conductance reaches of

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[338] *H. Komnick, "Chloride Cells and Chloride Epithelia of Aquatic Insects,"* International Review of Cytology, *49:285-328, 1977.*

[339] *N.N. Kapoor, "Osmotic Regulation and Salinity Tolerance of the Stonefly Nymph,* Paragnetina media," Journal of Insect Physiology, *25:17-20, 1979.*

[340] *C. Ellis, R. Champlin, and H.G. Stefan, "Density Current Intrusions in and Ice-covered Urban Lake,"* Journal of the American Water Resources Association, *33:1,363-1,374, 1997.*

[341] *Hintz and Relyea 2019,* op. cit.

[342] *B.J. Kefford, G.L. Hickey, A. Gasith, E. Ben-David, J.E. Dunlop, C.G. Palmer, K. Allan, S.C. Choy, and C. Piscart, "Global Scale Variation in the Salinity Sensitivity of Riverine Macroinvertebrates: Eastern Australia, France, Israel and South Africa,"* PLoS One*, 7:e.35224, 2012; Hassell et al. 2006,* op. cit.

[343] *Cañedo-Argüelles et al. 2013,* op. cit. *and references therein.*

[344] *S. Stranko, R. Bourquin, J. Zimmerman, M. Kishiwagi, M. McGinty, and R. Klauda,* Do Road Salts Cause Environmental Impacts? *Maryland Department of Natural Resources, 2013.*

[345] *Cañedo-Argüelles et al. 2013,* op. cit. *and references therein.*

[346] *C. Piscart, P.Usseglio-Poatera, J.-C. Moreteau, and J.-N. Beisel, "The Role of Salinity in the Selection of Traits of Freshwater Invertebrates,"* Archiv *für* Hydrobiologie*, 166:185-198, 2006; E. Szocz, E. Coring, J. Bathe, and R.B. Schafer, "Effects of Anthropogenic Salinization on Biological Traits and Community Composition, of Stream Macroinvertebrates,"* Science of the Total Environment, 468-469:943-949, 2014.

these rivers tended to incubate their eggs internally, conduct gas exchange through gills, produce multiple broods of offspring over a year, feed by shredding leaves and other large particulate organic matter, and have a longer life cycle. Macroinvertebrates found in the low specific conductance reaches tended to deposit their eggs in clutches in the environment, exchange gases through their body walls, produce only one brood per year, and have a shorter life cycle. The same studies also saw taxonomic differences that were associated with the level of specific conductance, with crustacea and some mollusks being more common and mayflies, stoneflies, and caddisflies being less common in stream reaches with higher specific conductance.

Possession of certain traits may account for the sensitivity of freshwater mussels and mussel populations to chloride salts and salinity for several reasons. First, they maintain the lowest internal salt concentration of any animal.[347] Although this results in their having lower energy requirements for ion regulation, it makes them more sensitive to environmental concentrations of salts than other animals.[348] They are also sessile and cannot easily escape to another part of the waterbody when exposed to high salt concentrations. Their ability to close their shells to avoid elevated salt concentrations is a temporary solution. Ultimately, metabolic requirements such as the need to acquire oxygen or excrete wastes will force them to reopen their shells.[349] As a result, closing their shell does not provide protection from extended periods of increased salinity or chloride concentration. Freshwater mussels also have a complicated life history. Their larvae, called glochidia, are obligate parasites on fish hosts.[350] Changes in the abundance of these hosts as a result of increased chloride concentration can affect recruitment of new mussels into the adult population.[351] Finally, they are long lived, with some species having life spans in excess of a century. Because of this, adult mussels can persist in a waterbody for decades despite a lack of recruitment. This makes it hard to recognize that a population is declining.[352]

Types of Effects of Chloride Salts and Salinity on Macroinvertebrates

Exposure to chloride, chloride salts, or salinity has been found to cause a variety of sublethal effects in macroinvertebrates. While different effects have been observed in different species, these effects fall into three broad categories: changes in behavior, changes in growth and development, and impacts on reproduction.

Effects of Chloride Salts and Salinity on Macroinvertebrate Behavior

Behavioral effects of exposure to chlorides include changes to feeding rates, changes in locomotion, and induction of invertebrate drift. Examples of changes in feeding rates have been observed in clams and mussels. The fingernail clam *Musculium transversum* beats its lateral cilia to bring food and oxygenated water to itself and carry wastes away. Impairment of ciliary beating is a sign of stress and can be detrimental to these clams. In eight-day experiments, exposure to potassium chloride impaired ciliary beating.[353] The rate of beating decreased as the concentration of potassium chloride increased. The impact of exposure may be permanent. When large clams were exposed to potassium chloride and subsequently placed in freshwater, the beating rates did not recover. A more complicated effect of chloride salts on feeding rates was observed with exposure of a unionid mussel to sodium chloride.[354] Over shorter exposure periods or intermittent exposures at low or moderate concentrations, the mussel *Anodonta anotina* increased its

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[347] *P. Wilmer, G. Stone, and I. Johnson,* Environmental Physiology of Animals (second edition), *Blackwell, Malden, Massachusetts, 2005.*

[348] *L.F. Gainey and M.J. Greenberg, "Physiological Basis of the Species Abundance-Salinity Relationship in Molluscs: A Speculation,"* Marine Biology*, 40-41-49, 1977.*

[349] *C.J. Blakeslee, H.S. Galbraith, L.S. Robertson, and B. St. John White, "The Effects of Salinity Exposure on Multiple Life Stages of a Common Freshwater Mussel,* Elliptio complanata," Environmental Toxicology and Chemistry*, 32:2,849-2,854, 2013.*

[350] *M.C. Barnhart, W.R. Haag, and W.N. Roston, "Adaptations to Host Infection and Larval Parasitism in Unionoida,"* Journal of the North American Benthological Society*, 27:370-394, 2008.*

[351] Ibid.

[352] *D.L. Strayer, J.A. Downing, W.R. Haag, T.L. King, J.B. Layzer, T.J. Newton, and S.J. Nichol, "Changing Perspectives on Pearly Mussels, North America's Most Imperiled Animals,"* BioScience*, 54:429-439, 2004.*

[353] *K.B. Anderson, R.E. Sparks, and A.A. Paparo,* Rapid Assessment of Water Quality Using the Fingernail Clam *Musculium transversum, University of Illinois Water Resources Center Report No, 133, April 1978.*

[354] *J.T. Hartmann, S. Beggel, K. Auershald, B.C. Stoeckle, and J. Geist, "Establishing Mussel Behavior as a Biomarker in Ecotoxicology,"* Aquatic Toxicology*, 170:297-288, 2016.*

filtration rate, but over longer exposure periods at higher concentrations its filtration rate decreased. The authors suggested that the increase in filtration rates at lower concentrations may reflect a need for mussels to flush salt from their bodies. Prolonged reductions in feeding rates by macroinvertebrates can reduce the energy that the organisms have available for growth and reproduction.

Exposure to chloride salts can also adversely affect locomotion in macroinvertebrates. For example, the swimming performance of the amphipod *Gammarus subaegensis* exposed to calcium chloride was reduced relative to that of untreated animals.[355] Performance decreased as calcium chloride concentration increased. About half the ampipods showed reduced swimming performance at a calcium chloride concentration of 2,850 mg/l.

Increases in chloride concentrations alter invertebrate drift behavior in streams and rivers. Drift is a common behavior in which macroinvertebrates living on or in the substrate or on aquatic macrophytes enter the water column and are transported downstream in flow. Normally, this serves as a means of avoiding predators and dispersing into downstream areas. Higher chloride concentrations can lead to an increase in drift behavior. One field study found that drift behavior increased when chloride concentrations exceeded 1,000 mg/l.[356] A mesocosm experiment examining a mixed macroinvertebrate community found that the number of organisms drifting increased with higher sodium chloride concentration.[357] An example of this is seen in another study in which chloride concentrations of 606 mg/l, 1,516 mg/l, and 6,066 mg/l led to 13 percent, 45 percent, and 58 percent increases, respectively, in drift in the amphipod *Gammarus pseudolimnaeus*.[358] This chloride-induced increase in drift behavior could potentially reduce the abundance of macroinvertebrates in reaches of streams and rivers impacted by elevated chloride concentrations.

Behavioral changes induced by exposure to chloride salts can potentially affect the viability of macroinvertebrate populations. Reductions in feeding rate can lead to slower growth and less reproduction, which can ultimately reduce the number of new individuals recruited into the population. In addition, impairment of locomotion and alteration of drift behavior can increase exposure of the affected organisms to predators. Increases in drift behavior above normal levels can lead to removal of some macroinvertebrate species from chloride-impacted stream reaches. If the effects are great enough, the abundance of sensitive species of macroinvertebrates in chloride-impacted habitats may be greatly reduced. In some instances, sensitive species may be extirpated from highly impacted habitats.

Effects of Chloride Salts and Salinity on Macroinvertebrate Development

Chloride and chloride salts can affect growth and development of freshwater macroinvertebrates. Impacts that have been reported include reductions in growth, lengthening the period needed to complete larval development, reductions in the size of adults, induction of developmental deformities, and alterations of sexual dimorphism and sex ratios. Increased concentrations of chloride or salinity and increased specific conductance have been reported to reduce growth in several species of macroinvertebrates. For example, reductions in the final biomass attained by larvae of the midge *Chironomus dilutus* after 28 days of growth were observed at a chloride concentration of 2,133 mg/l, with a 50 percent reduction seen at a concentration of 3,047 mg/l.[359] A similar reduction in growth with increasing chloride concentration has been reported in mayflies. Over 90 days, first instar nymphs of the burrowing mayfly *Hexagenia limbata* achieved higher biomass at a salinity of 0 mg/l than at 2,000 mg/l or 4,000 mg/l.[360] Growth reductions in mayflies have been

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[355] *M.J. Baek, T.J. Yoon, D.G. Kim, C.Y. Lee, K. Cho, and Y.J. Bae, "Effects of Road Deicer Runoff on Benthic Macroinvertebrate Communities in Korean Freshwaters with Toxicity Tests of Calcium Chloride ($CaCl_2$),"* Water, Air, and Soil Pollution*, 225:e1961, 2014.*

[356] *R.A. Crowther and H.B.N. Hynes, "Effect of Road Deicing Salt on Drift of Stream Benthos,"* Environmental Pollution, *14:113-126, 1977.*

[357] *M. Cañedo-Argüelles, T.E. Grantham, I. Perrée, M. Rieradevall, R. Céspedes-Sánchez, and N. Prat, "Response of Stream Invertebrates to Shot-term Salinization: A Mesocosm Approach,"* Environmental Pollution, *166:144-151, 2012.*

[358] *B.J. Blasius and R.W. Merritt, "Field and Laboratory Investigations on the Effects of Road Salt (NaCl) on Stream Macroinvertebrate Communities,"* Environmental Pollution*, 120:219-231, 2002.*

[359] *Elphick et al. 2011,* op. cit.

[360] *M.A. Chadwick and J.W. Feminella, "Influence of Salinity and Temperature on the Growth and Production of a Freshwater Mayfly in the Lower Mobile River, Alabama,"* Limnology and Oceanography*, 46:532-542, 2001.*

reported occurring as a result of several different chloride salts. A series of 14-day growth experiments found 25 percent reductions in growth in the mayfly *Neocloeon tringulifer* when exposed to sodium chloride concentrations of 229 mg/l or potassium chloride concentrations of 356 mg/l.[361] Similarly, 20-day growth experiments found reductions in daily growth rates when the same mayfly species was exposed to a mixture of sodium chloride and calcium chloride.[362] Reductions began to be seen when specific conductance was above 363 µS/cm. Finally, the lengths, widths, and masses attained by the snail *Heliosoma trivovlis* decreased with increasing specific conductance.[363]

Chloride- and salinity-induced reductions in growth can lengthen the time required for freshwater macroinvertebrates to complete larval development. For example, over 7-day experiments the number of molts undergone by the mayfly *Isonychia bicolor* decreased with increasing chloride concentration. This effect appeared to be dose dependent, with higher chloride concentrations leading to fewer molts.[364] Since the number of molts is an indication of the amount of growth, this result indicates that increasing chloride concentrations led to slower growth. Similarly, the time needed for first instar larvae of the mosquito *Culiseta incidens* to complete larval development and form pupae got longer with increasing concentration of sodium chloride.[365]

In some instances, slower growth and longer developmental periods resulting from exposure to chloride salts may occur despite increased food consumption. An experiment exposing the isopod *Lirceus* sp. to sodium chloride found that the amount the isopod grew was 12 percent lower at a chloride concentration of about 215 mg/l than it was at a concentration of about 4 mg/l despite the isopods in the high salt treatment eating about 74 percent more.[366] At the same time, there appeared to be no change in the efficiency of the isopods' assimilation of food. This suggests that the increased consumption was respired, potentially to accommodate higher metabolic demands for dealing with osmotic stress. The reduction in growth rate may reflect diversion of energy in the organism from growth to meeting these metabolic demands.

In insects that undergo complete metamorphosis, increasing salinity can also affect the size and weight of the insects when they pupate. For example, a study found that the dry weight of pupae of the mosquito *Aedes aegypti* decreased with increasing salinity.[367] Pupation does not generally occur until insects gain a critical mass of internal nutrient stores.[368] Because adult insects are encased in an exoskeleton and cannot molt, adult size and weight are determined by the weight of the pupa. The size that pupae attain is based on the ability of larvae to gather and retain nutrients during the larval period. As a result, increased energy expenditures or reduced nutrient assimilation due to physiological impacts from higher salt concentrations require insect larvae to either increase their feeding rates, experience longer larval periods, or attain reduced adult body sizes.

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[361] *K.A. Struewing, J.M. Lazorchak, P.C. Weaver, B.R. Johnson, D.H Funk, and D.B. Buchwalter, "Part 2: Sensitivity Comparisons of the Mayfly* Centroptilum triangulifer *to* Ceriodaphnia dubia *and* Daphnia magna *Using Standard Reference Toxicants; NaCl, KCl, and $CuSO_4$,"* Chemosphere*, 139:597-603, 2015.*

[362] *B.R. Johnson, P.C. Weaver, C.T. Nietch, J.M. Lazorchak, K.A. Struewing, and D.H. Funk, "Elevated Major Ion Concentrations Inhibit Larval Mayfly Growth and Development,"* Environmental Toxicology and Chemistry*, 34:167-172, 2015.*

[363] *J.G. Suski, C.J. Solace, and R. Patiño, "Species-Specific and Transgenerational Responses to Increasing Salinity in Sympatric Freshwater Gastropods,"* Environmental Toxicology and Chemistry*, 31:2,517-2,524, 2012.*

[364] *B.S. Echols, R.J. Currie, D.S. Cherry, and J.R. Voshell, "Seasonal Availability and Sensitivity of Two Field-Collected Mayflies for the Development of a Standardized Toxicity Test,"* Environmental Monitoring and Assessment*, 185:1,341-1,353, 2013.*

[365] *F.C. Lee, "Effect of Various Sodium Chloride Concentrations on the Development of the Mosquito* Culiseta incidens *(Thompson),"* Mosquito News*, 33:78-83, 1973.*

[366] *M. Tyree, N. Clay, S. Polaskey, and S. Entrekin, "Salt in Our Streams: Even Small Sodium Additions Can Have Negative Effects on Detritivores,"* Hydrobiologia*, 775:109-122, 2016.*

[367] *T.M. Clark, B.J. Flis, and S.K. Remold, "Differences in the Effects of Salinity on Larval Growth and Developmental Programs of a Freshwater and a Euryhaline Mosquito Species (Insecta: Diptera, Culicidae)*, The Journal of Experimental Biology*, 207:2,289-2,295, 2004.*

[368] *A.N. Clements,* The Biology of Mosquitoes. Volume 1. Development, Nutrition, and Reproduction*, CABI Publishing, Wallingford, U.K., 2000.*

Developmental deformities in macroinvertebrates have also been associated with increased salinity. For example, wing deformities were observed in *Chironomus* midges emerging from pupae that were incubated at a specific conductance equal to or greater than 2,500 μS/cm.[369] Similarly, malformations were seen in hatchlings of the snail *Heliosoma trivolvis* at specific conductance greater than 1,500 μS/cm.[370] The percentage of malformed snails increased with specific conductance, reaching 17 percent at a specific conductance of 3,750 μS/cm.

Exposure to chloride salts can induce other developmental effects. High concentrations of chloride salts can affect sex ratios and sexual dimorphism in some macroinvertebrate species. An example of this comes from an experiment in which larvae of the midge *Chironomus riparius* were exposed to different concentrations of sodium chloride while under a temperature regime simulating a spring thaw.[371] When larvae were exposed to 0 mg/l sodium chloride, emerging adult females were larger than emerging adult males. This is normal for this species. The ratio of males to females in the emerging midges was one to one. The average time to complete development was about 48 days. When larvae were exposed to 5,000 mg/l sodium chloride, emerging adult females were the same size as emerging adult males. The ratio of males to females was two to one. The average time to complete development was about 59 days.

Impacts of chloride and chloride salts on growth and development can potentially affect the viability of macroinvertebrate populations. This can happen in a variety of ways. In many macroinvertebrate species, the number of eggs a female can produce is a function of her size, with larger females producing more eggs. In these species, reductions in the size of females resulting from increased ambient concentrations of chloride will lead to fewer eggs being laid. Coupled with other impacts of chloride, this can lead to decreases in the abundance of impacted macroinvertebrate species. For those species that reproduce only once during the year, larval forms such as aquatic insect nymphs have a limited period in which to achieve adulthood and reproduce. If the developmental period of a species is lengthened too much, there may not be adequate time remaining in the season for adults to emerge and reproduce before the onset of winter. This can also lead to fewer eggs being laid and a decrease in the abundance of the species. Similar reductions in abundance may result from a large enough percentage of the population having deformities or a skewed sex ratio.

Effects of Chloride Salts and Salinity on Macroinvertebrate Reproduction

Chloride and chloride salts can affect freshwater macroinvertebrate reproduction. Examples of impacts include reductions in reproductive output that consists of the number of offspring produced, delay or prevention of reproduction, reduction in the motility of sperm, slower egg development, reduced hatching success, and unsuccessful attachment of mussel glochidia to fish hosts. For example, in 28-day tests, exposure to chloride resulted in reductions in reproductive output in two annelid worm species.[372] Reductions were observed in the blackworm *Lumbriculus variegatus* at a chloride concentration of 366 mg/l, with 50 percent of the exposed animals showing lower reproduction at 958 mg/l. Similarly, reductions were observed in the sludge worm *Tubifex tubifex* at a chloride concentration of 462 mg/l, with 50 percent of the exposed animals showing reproductive reductions at 752 mg/l. Another study showed that the snail *Heliosoma trivolvis* did not reproduce at specific conductance above 3,000 μS/cm and that the onset of reproduction was delayed at specific conductance levels above 2,000 μS/cm.[373]

Exposure to sodium chloride with chloride concentrations of about 580 mg/l has also been reported to suppress motility of sperm in the zebra mussel, *Dreissena polymorpha*.[374] Such suppression prevents sperm from reaching eggs and limits fertilization.

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[369] *Hassell et al. 2006,* op. cit.

[370] *Suski et al. 2012,* op. cit.

[371] *D.W. Lob and P. Silver, "Effects of Elevated Salinity from Road Deicers on* Chironomus riparius *at Environmentally Realistic Springtime Temperatures,"* Freshwater Science*, 31:1,078-1,087, 2012.*

[372] *Elphick et al. 2011,* op. cit.

[373] *Suski et al. 2012,* op. cit.

[374] *A. Ciereszko, K. Dabrowski, B. Piros, M. Kwasnik, and J. Glogowski, "Characterization of Zebra Mussel (*Dreissena polymorpha*) Sperm Motility: Duration of Movement, Effects of Cations, pH and Gossypol,"* Hydrobiologia*, 452:225-232, 2001.*

Exposure to chloride salts and salinity can also increase egg development time and reduce hatching of macroinvertebrate eggs. For instance, eggs of the snail *Heliosoma trivolvis* took longer to hatch at specific conductance levels above 250 μS/cm than they took at lower values.[375] This suggests that exposure to higher salinity delayed embryonic development. The fraction of eggs of the snail *Glyptophysa gibbosa* that hatched decreased with increasing specific conductance.[376] Similarly, hatching of the eggs of the common backswimmer, *Notonecta glauca* decreased with increasing specific conductance.[377]

Exposure to chloride salts can also reduce attachment of freshwater mussel glochidia to fish hosts. As previously described, mussel glochidia must attach to a fish host in order to continue development. Attachment is controlled by an ion gradient which can induce clamping behavior, which is important for attaching.[378] Elevated salinity can induce premature clamping and can reduce the number of glochidia that are able to successfully attach to fish hosts.[379] For example, the percentage of glochidia in the species *Anodonta anatina* that successfully attached to fish decreased from 40 percent at a chloride concentration of 130 mg/l to 7 percent at a chloride concentration of 2,909 mg/l.[380] Similarly, at a sodium chloride concentration of 3,000 mg/l, attachment of glochidia of the mussel *Elliptio complanata* was only 11 percent of the level seen in controls.[381]

Impacts of chloride and chloride salts on reproduction can potentially affect the viability of macroinvertebrate populations. Lower reproductive output, reductions in the motility of sperm, slower egg development, reduced hatching success, and reduced attachment of mussel glochidia to fish hosts can all reduce the recruitment of adults into the population. Over the long term, this can reduce species abundance.

Fish

Freshwater fish are animals with backbones that live all life stages entirely in water. Freshwater fish vary in size. For example, the least darter (*Etheostoma microperca*) is one of the smallest fish in Wisconsin. Typically, its length is only one to one-and-a-half inches. The lake sturgeon (*Acipenser fulvescens*) is one of the largest fish in the State and typical lengths range between 59 and 71 inches. The maximum length for a lake sturgeon reported in Wisconsin is 98 inches. Some examples of fish reported to be impacted by chloride salts are shown in Figure 3.6.

Fish perform several roles in aquatic communities. They occupy all consumer categories in aquatic food webs. This includes detritivores; herbivores that feed on plankton, periphyton, or macrophytes; and predators that feed on zooplankton, macroinvertebrates, or other fish. Some fish are generalists that feed on an array of food items. Fish continue to grow throughout their entire lives. As a result, the diet of some fish species changes with age and size. For example, some species shift from feeding on zooplankton to macroinvertebrates to other fish as they grow. This reflects an aspect of fish biology that most fish consume their prey whole. The largest prey fish can consume is limited by the size of their gape and organisms that are larger than this are not susceptible to predation. As fish grow their gape gets larger as does the size of the prey they can ingest.

Fish can also serve as prey in aquatic communities and the major predator of fish is other fish. Large predatory invertebrates may also feed on fish larvae and fry. In addition, some mammals and birds specialize as fish predators.

Fish also have an important role in outdoor recreation in Wisconsin. People in the State commonly fish for trout and salmon; other sport fish such as largemouth and smallmouth bass, northern pike, walleye, and

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[375] *Suski et al. 2012,* op. cit.

[376] *Kefford et al. 2007,* op. cit.

[377] *H. Komnick and W. Wichard, "Chloride Cells of Larva of* Notonecta glauca *and* Naucoris cimicoides *(Hemiptera, Hyrocorisae) Fine Structure and Cell Counts at Different Salinities,"* Cell and Tissue Research*, 156:539-549, 1975.*

[378] *G. Lefeve and W.C. Cutis, "Studies on the Reproduction and Artificial Propagation of Freshwater Mussels,"* Bulletin of the United States Bureau of Fisheries*, 30:105-201, 1912.*

[379] *S. Beggel and J. Geist, "Acute Effects of Salinity Exposure on Glochidia Viability and Host Infection of the Freshwater Mussel* Anodonta anatina*, (Linnaeus, 1758),* Science of the Total Environment*, 502:659-665, 2015.*

[380] Ibid.

[381] *Blakeslee et al. 2013,* op. cit.

Figure 3.6
Examples of Fish Reported to be Impacted by Chloride Salts

Source: Flickr and WDNR

muskellunge; panfish such as bluegill, yellow perch, and crappies; and whitefish. In addition, people also fish for rough fish such as suckers and carp. Recreational fishing has a large economic impact on Wisconsin. The Wisconsin Department of Natural Resources (WDNR) estimates that fishing generates almost $2.3 billion in economic activity annually.

Fish Sensitivity to Chloride and Salinity

Some general features of the biology of fish can make them sensitive to impacts from chloride salts and salinity in general. Freshwater fish generally maintain their body fluids at an ionic concentration of about 10,000 mg/l, which is far higher than that in the environment.[382] They gain water and lose ions passively, with sodium and chloride ions passing through their gills, oral membranes, intestinal surface, and skin. Fish conduct osmotic regulation through active transport of ions into their cells across their oral membranes and gill surfaces and the excretion of large amounts of dilute urine. Fish must expend energy to use these regulatory processes. This reduces the energy that is available for growth and reproduction and can lead to a variety of impacts on the organism that will be discussed later in this section.

[382] *Hart et al. 1991,* op. cit.

Life stage is an important consideration when examining the effects of chloride salts and salinity on fish.[383] Early life stages of fish are often more sensitive to chloride salts and salinity than adults. Some examples of early life stages in salmon are shown in Figure 3.7. Larval fish lack adult osmoregulatory capabilities. Trout and salmon, for example, enter a nonfeeding alevin stage after hatching. These larvae lack fully developed structures such as gills and kidneys that help fish cope with environmental contaminants and regulate the ion concentration of their internal fluids.[384] This is typical of newly hatched fish of all species. In addition, larval fish have a greater surface to volume ratio than adult fish that provides a relatively greater area for movement of water and ions across their skin. Larval fish also have fewer gill filaments. These structures are involved in the transfer of ions and water across the gills.[385] Larval fish are unable to move away from contaminated habitats. As a result of all these factors, larval fish are less tolerant of chloride salts and salinity than either eggs or adults.

Timing of reproduction can also affect the sensitivity of some fish species to chloride salts and salinity. Larval fish and fry of some species are present in streams or lakes during spring snowmelt and are therefore exposed to high salinity and concentrations of chloride.

Types of Impacts of Chloride Salts on Fish

Exposure to chloride, chloride salts, or salinity has been found to cause a variety of sublethal effects in fish. While different effects have been observed in different species, these effects fall into four broad categories: changes in metabolism, changes in behavior, changes in growth, and impacts on reproduction. It is also important to recognize that relatively few fish species have been examined and most of those are species that are easily reared or kept in a laboratory setting. For example, when adult rainbow trout (*Oncorhynchus mykiss*) are properly acclimated, they may be able to physiologically compensate for higher salinity.[386] Other obligate freshwater salmonids may lack this ability.[387]

Impacts of Chloride Salts and Salinity on Fish Metabolism

Increases in salinity can lead to changes in metabolic rates in fish. One study found that over one week of exposure, the metabolic rates of redbelly dace (*Phoxinus erythrogaster*) and northern studfish (*Fundulus catentus)* rose with increasing salinity.[388] The authors suggested that the increase in metabolism may reflect energy use by the fish to repair damage from salinity or to excrete salt. Another study that exposed goldfish (*Carassius auratus*) to a range of salinities found that the conversion of food mass to fish mass was lower at salinities greater than about 4,000 mg/l.[389] It is likely that the additional food these fish consumed was respired to provide energy to compensate for higher salinity. A more complicated relationship between salinity and metabolic rates was seen in a study with fathead minnows (*Pimephales promelas*).[390] In a 24-hour test, the minnows' metabolic rate was lower at salinities of 200 mg/l to 400 mg/l than it was at lower salinities. The authors suggested that this reflected reduced activity by the fish at higher salinities. Researchers observed

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383 *W.D. Hintz and R.A. Relyea, "Impacts of Road Deicing Salts on the Early-Life Growth and Development of a Stream Salmonid: Salt Type Matters,"* Environmental Pollution*, 223:409-415, 2017.*

384 *Hintz and Relyea,* Environmental Pollution *2017,* op. cit.

385 *Hart et al. 1991,* op. cit.

386 *J.D. Morgan and G.K. Iwama, "Effects of Salinity on Growth, Metabolism, and Ion Regulation in Juvenile Rainbow and Steelhead trout (*Oncorhynchus mykiss*) and Fall Chinook Salmon (*Onchorhynchus tshawyscha*),"* Canadian Journal of Fisheries and Aquatic Sciences*, 48:2,083-2,094, 1991.*

387 *S.D. Blair, D. Matheson, Y. He, and G.G. Goss, " Reduced Salinity Tolerance in Arctic Grayling (*Thymallus arcticus*) Is Associated with Rapid Development of a Gill Interlamellar Cell Mass: Implications of High-Saline Spills on Native Freshwater Salmonids,"* Conservation Physiology, *4: doi: 10.1093/conphys/cow010, 2016.*

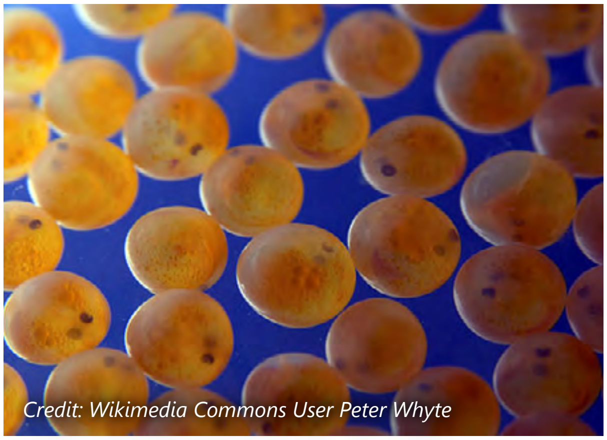
388 *C. Toepfer and M. Barton, "Influence of Salinity on the Rates of Oxygen Consumption in Two Species of Freshwater Fishes,* Phoxinus erythrogaster *(Family Cyprinidae) and* Fundulus catenatus *(Family Fundulidae*)," Hydrobiologia, *242:149-154, 1992.*

389 *R.K Luz, R.M. Martínez-Álvarez, N. DePedro, and M.J. Delgado, " Growth, Food Intake Regulation, and Metabolic Adaptations in Goldfish* (Carassius auratus*) Exposed to Different Salinities,"* Aquaculture*, 276:171-178, 2008.*

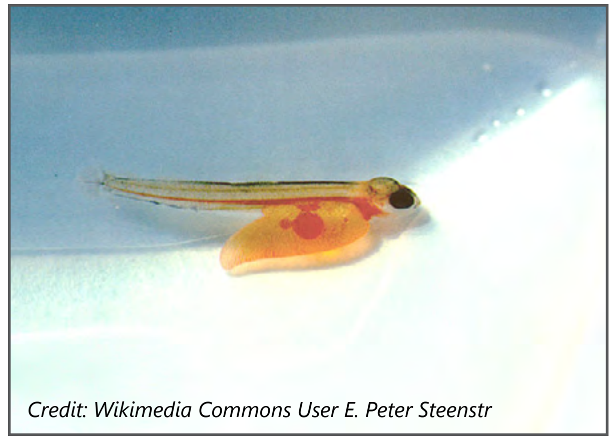
390 *D. H. Pistole, J.D. Peles, and K. Taylor, "Influence of Metal Concentrations, Percent Salinity, and Length of Exposure on the Metabolic Rate of Fathead Minnows (*Pimephales promelas*),"* Comparative Biochemistry and Physiology, Part C*, 148:48-52, 2008.*

Figure 3.7
Some Early Life Stages of Fish

Salmon Eggs	Salmon Alevins (Sac Fry)



Credit: Wikimedia Commons User Peter Whyte



Credit: Wikimedia Commons User E. Peter Steenstr

Source: Wikimedia Commons

a different result in a 96-hour test for fathead minnows.[391] At lower salinities, the minnows' metabolic rate increased with increasing salinity, plateauing at a salinity of 100 mg/l. This plateaued rate then lowered when salinities exceeded 400 mg/l. The increase in metabolic rate with salinity is what would be expected if the fish required more energy to maintain osmoregulation. The decrease in metabolic rate at higher salinities may have resulted from the fish reaching the upper limits of their ability to compensate for stresses related to salinity.[392] While the fathead minnows were able to survive, they may not have been able to maintain their metabolic rate in the presence of higher salinity. These studies indicate that increases in salinity, including those imposed by higher chloride concentrations, can impose additional metabolic costs on fish which can reduce the scope of activity for fish and may lead to reductions in growth or reproduction.

Impacts of Chloride Salts and Salinity on Fish Behavior

Behavioral impacts of salinity that have been reported in fish include general decreases in activity, impaired locomotion, and reductions in antipredator behaviors. Levels of activity in goldfish (*Carassius auratus*) during the day were reduced as compared to controls at all salinities equal to or greater than 2,000 mg/l.[393] Interestingly, exposure to salinity up to 10,000 mg/l had no effect on the goldfish level of activity during night-time. In a seven-day experiment, fathead minnow (*Pimephales promelas*) larvae that were exposed to sodium chloride showed impaired swimming behavior at concentrations of 4,000 mg/l and 8,000 mg/l.[394] Finally, the amounts of antipredator behavior exhibited by fathead minnow exposed to salinity decreased when salinity reached and exceeded 8,000 mg/l.[395]

[391] Ibid.

[392] *P. Calo, "Physiological Costs of Combating Chemical Toxicants: Ecological Implications,"* Comparative Biochemistry and Physiology, Part C, *100:3-9, 1991.*

[393] *Luz et al. 2008,* op. cit.

[394] *Baek International, "Ecotoxicity Test Results," 1999, cited in Evans and Frick 2001,* op. cit.

[395] *Z. Hoover, M.C.O. Ferrari, and D.P. Chivers, "The Effects of Sub-Lethal Salinity Concentrations on the Anti-Predator Responses of Fathead Minnows,"* Chemosphere, *90:1,047-1,052, 2013.*

Impacts of Chloride Salts and Salinity on Fish Growth

Chloride salts and salinity can affect the growth of freshwater fish. Several early life stages can be affected. For example, over a 470-degree day exposure,[396] Atlantic salmon (*Salmo salar*) alevins (nonfeeding larvae) exposed to road salt consisting of over 98 percent sodium chloride at a concentration 1,000 mg/l showed less growth than those in a control treatment.[397] The rate at which these larvae used their yolk sacs also decreased with salt concentration, suggesting slower conversion of stored food mass to fish mass. Similar reductions in growth with increased chloride concentrations have been reported in newly hatched rainbow trout (*Onchorhynchus mykiss*).[398] Reductions in growth with higher sodium chloride concentrations have also been reported for fathead minnow (*Pimephales promelas*) larvae[399] and fry[400] and goldfish (*Carassius auratus*).[401]

Growth reductions related to chloride salts may be occurring in local streams. When fathead minnow (*Pimephales promelas*) larvae were grown in seven-day bioassays using water from 14 Milwaukee-area streams, the mean weight of the larvae decreased with increasing chloride concentration.[402] These effects began to be seen above chloride concentrations of 2,940 mg/l. A bioassay using water collected on different dates from Wilson Park Creek in the City of Milwaukee showed similar results, with growth reductions appearing above a chloride concentration of 2,920 mg/l.[403]

The cation associated with chloride can influence whether an effect on fish growth occurs and the magnitude of any effect. A 25-day experiment examined growth of newly hatched rainbow trout (*Onchorhynchus mykiss*) exposed to three chloride salts with chloride concentrations ranging from 25 mg/l to 3,000 mg/l.[404] Magnesium chloride had no effect on growth at any concentration tested. Sodium chloride reduced growth at concentrations greater than 860 mg/l. A sodium chloride concentration of 3,000 mg/l resulted in a 9 percent reduction in length and a 27 percent reduction in mass of young rainbow trout. as compared to controls. Calcium chloride reduced growth at concentrations equal to or greater than 860 mg/l. A calcium chloride concentration of 3,000 mg/ resulted in an 11 percent reduction in length and a 31 percent reduction in mass of young rainbow trout as compared to controls.

It should be noted that the growth of some fish species may be stimulated by moderate concentrations of chloride salts. For example, the growth of bridle shiner minnows (*Notropis bifrenatus*) was enhanced by chloride concentrations of 500 mg/l to 1,000 mg/l.[405] Larvae of common carp (*Cyprinus carpio*) show increasing rates of growth with increasing salinity over the range 0 mg/l to 3,000 mg/l.[406] Similarly, the highest hatching rate of channel catfish (*Ictalurus punctatus*) eggs occurred at a sodium chloride concentration of 1,000 mg/l.[407]

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[396] *Degree days are a measure of total temperature exposure over time. The cited study measured exposure using degree days to control for the effect of temperature on alevin growth rates.*

[397] *Mahrosh et al. 2018,* op. cit.

[398] *Elphick et al. 2011,* op. cit.

[399] Ibid.*; Baek International 1995,* op. cit.

[400] *W.J. Birge, J.A. Black, A.G. Westerman, T.M. Short, S.B. Taylor, D.M. Bruser, and E.D. Wallingford,* Recommendations on Numerical Values for Regulating Iron and Chloride Concentrations for the Purpose of Protecting Warmwater Species of Aquatic Life in the Commonwealth of Kentucky, *Memorandum of Agreement No. 5429, Kentucky Natural Resources and Environmental Protection Cabinet, 1985.*

[401] *Luz et al. 2008,* op. cit.

[402] *S.R. Corsi, D.J. Grazcyk, S.W. Geis, N.L. Booth, and K.D. Richards, "A Fresh Look at Road Salt: Aquatic Toxicity and Water Quality Impacts on Local, Regional, and National Scales,"* Environmental Science & Technology*, 44:7,376-7,382, 2010.*

[403] Ibid.

[404] *Hintz and Relyea 2017* Oecologia*,* op. cit.

[405] *Hintz et al. 2017,* op. cit.

[406] *T.J. Lam and R. Sharma, "Effects of Salinity and Thyroxine on Larval Survival, Growth and Development in the Carp,* Cyprinus carpio*,"* Aquaculture*, 44::201-212, 1985.*

[407] *C.R. Weirich and T.R. Tierach, "Effects of Environmental Sodium Chloride on Percent Hatch, Yolk Utilization, and Survival of Channel Catfish Fry,"* Journal of the World Aquaculture Society*, 28:289-296, 1997.*

There are potential ecological consequences that could result from reductions in growth rates in fish due to elevated chloride concentrations or salinity.[408] A result of reduced growth rates is that fish will spend more time in early life stages that could lead to increased risk of predation due to the fish being small for a longer period. Reduced growth rates could also affect the availability of food to young fish. Size is an important factor that determines what food is available to fish. Fry can only feed on prey that are within a narrow range of sizes. In some instances, slower growth could result in fry depleting available food in the proper size range as development proceeds. These two impacts could potentially reduce recruitment of fish into the adult population; however, fish have the capacity to accelerate growth at other life stages to compensate for poor growth at early stages.[409] As a result, growth could accelerate as fish age or water quality improves.

Impacts of Chloride Salts and Salinity on Fish Reproduction

Chloride and chloride salts can affect freshwater fish reproduction. Impacts include prevention of fertilization, low survival of eggs, delays in egg hatching, and interference with early development. Elevated salinity can prevent fertilization of freshwater fish eggs by reducing the motility of their sperm. Depending on species, the upper limit of salinity for successful fertilization in freshwater fish is between 9,000 mg/l and 15,000 mg/l.[410]

Exposure to chloride salts can also affect egg survival. For example, exposure of Atlantic salmon (*Salmo salar*) eggs to sodium chloride at concentrations ranging between 5,000 mg/l and 10,000 mg/l during fertilization resulted in low survival of the eggs.[411] Hatching was also delayed in those eggs that did survive. Higher egg survival was observed when the chloride exposure occurred after fertilization. These effects on eggs may be due, in part, to impacts of salinity on early development. For example, embryos in zebrafish (*Danio rerio*) eggs incubated at salinities greater than 4,000 mg/l were unable to undergo gastrulation.[412]

Elevated salinity can also induce production of deformed embryos in developing fish eggs. One way that this happens is through salinity's effects on early egg development. Once fish eggs are fertilized, they undergo a process of hardening of their outer membrane. This is accompanied by swelling of the egg. The swelling forms a perivitelline space within the egg that provides space for embryo formation and growth. These processes can be disrupted by high salinity. For example, in salmonid species hardening of the outer membrane and formation of the perivitelline space is inhibited when salinity is higher than about 3,000 mg/l.[413] Similarly, Atlantic salmon (*Salmo salar*) eggs showed reduced swelling at sodium chloride concentrations above 5,000 mg/l.[414] Since the volume of a fish embryo increases during development, a small perivitelline space can restrict development and lead to more deformities in hatched fish.[415] In some instances, the percentage of fish hatching that showed deformities rose with increasing salt concentration. This was seen in Atlantic salmon (see Table 3.16).[416] Examples of deformities observed included scoliosis, conjoined twins, coiled tails, and deformed yolk sacs.

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[408] *Hintz and Relyea* Environmental Pollution *2017,* op. cit.

[409] *M. Ali, A. Nicienza, and R.J. Wootton, "Compensatory Growth in Fishes: A Response to Growth Depression,"* Fish and Fisheries*, 4:147-190, 2003.*

[410] *A.E. Hogan and J.C. Nicholson, "Sperm Motility of Sooty Grunter* Hephaestus fulginosus *(Macleay) and Jungle Perch* Kujlia rupestris *(Lacepede) in Different Salinities,"* Australian Journal of Marine and Freshwater Research*, 38:523-528, 1987.*

[411] *Mahrosh et al. 2014,* op. cit.

[412] *M.S. Sawant, S. Zhang, and L. Li, "Effect of Salinity on Development of Zebrafish* Brachydanio rerio*,"* Current Science*, 81:1,347-1,350, 2001.*

[413] *Hart et al. 1991,* op. cit.

[414] *Mahrosh et al. 2014,* op. cit.

[415] *X. Li, E. Jenssen, and H.J. Fyhn, "Effects of Salinity on Egg Swelling in Atlantic Salmon (*Salmo salar*),"* Aquaculture*, 76:317-334, 1989; M. Keinanen, C. Tigerstedt, S. Peuranen, and P.J. Vuorinen, "The Susceptibility of Early Developmental Phases of an Acid-Tolerant and Acid-Sensitive Fish Species to Acidity and Aluminum,"* Ecotoxicology and Environmental Safety, *58:160-172, 2004.*

[416] *Mahrosh et al. 2018,* op. cit.

Impacts of chloride and chloride salts on reproduction can potentially affect the viability of fish populations. Reductions in the motility of sperm and fertilization, slower egg development, reduced hatching success, and inducement of deformities can all reduce the recruitment of adults into the fish population. Over the long term, this can reduce the species' abundance.

Table 3.16
Percentage of Atlantic Salmon Alevins Showing Deformities at Different Sodium Chloride Concentrations

Sodium Chloride Concentration (mg/l)	Percent of Eggs Showing Deformities
0	0
100	10
500	15
1,000	27

*Source: U. Mahrosh, M. Kleiven, S. Meland, B.O. Rosseland, B. Salbu, and H.-C. Teien, "Single and Multiple Stressor Effect of Road Deicing Salt (NaCl) and Copper (Cu) to Fertilization and Early Development Stages of Atlantic Salmon (*Salmo salar*) Alevins from Hatching to Swim-up,"* Journal of Environmental Sciences, *66:368-378, 2018*

Amphibians

Amphibians are four-limbed cold-blooded animals with backbones that have life histories that require the use of both aquatic and terrestrial habitats. Typically, adult amphibians lay their eggs in water and have aquatic larvae. As these larvae grow, they undergo metamorphosis to assume their adult form. The adults are either terrestrial or semiaquatic. Adult amphibians continue to grow throughout their lives. Life stages of two amphibian species are shown in Figure 3.8.

Two groups of amphibians are found in Wisconsin, anurans and caudates. Anurans include frogs, tree frogs, and toads. Adult anurans lack tails; these structures disappear during metamorphosis. Caudates include salamanders, newts, and mudpuppies and adults have tails throughout their lives. Examples of Wisconsin amphibians are shown in Figure 3.9.

Amphibians generally prefer cool, damp habitats. Because they can easily dry out, amphibians are generally restricted to high moisture environments. Many are also nocturnal for this reason.

Amphibians perform several roles in aquatic and terrestrial communities. An important feature of their biology is that they change trophic position over their life cycle.[417] Anuran larvae are primarily herbivorous or omnivorous, feeding on plankton, periphyton, and detritus. Grazing by tadpoles is an important process regulating the growth of aquatic algae. Caudate larvae are carnivorous, feeding on small aquatic animals such as macroinvertebrates, tadpoles, and other salamander larvae. Salamander larvae serve as the top predator in many ephemeral ponds. Adult amphibians are carnivorous, feeding on insects and other invertebrates. The prey organisms of many adult amphibians are terrestrial.

Amphibians also serve as prey to other organisms. They are high quality prey for predators such as birds, mammals, fish, and reptiles. Because they move between aquatic and terrestrial habitats during their life cycle, amphibians serve to link aquatic food webs to terrestrial food webs.

<u>Factors Affecting Amphibian Sensitivity to Chloride Salts and Salinity</u>

Some general features of the biology of amphibians can make them sensitive to impacts from chloride salts and salinity in general. The skin of amphibians lacks scales or other coverings and is highly permeable. The exchange of gases, water, and ions occurs across the skin. Amphibians constantly transport ions across their skin to maintain ion and water balance.[418] Beginning at metamorphosis, the skin of adult amphibians is capable of actively transporting both sodium and chloride ions into the body.[419] While diffusion of some ions may occur through their skin, in larvae the gills are the site of active transport of sodium and chloride ions.[420] This active transport requires that the organism expend energy.

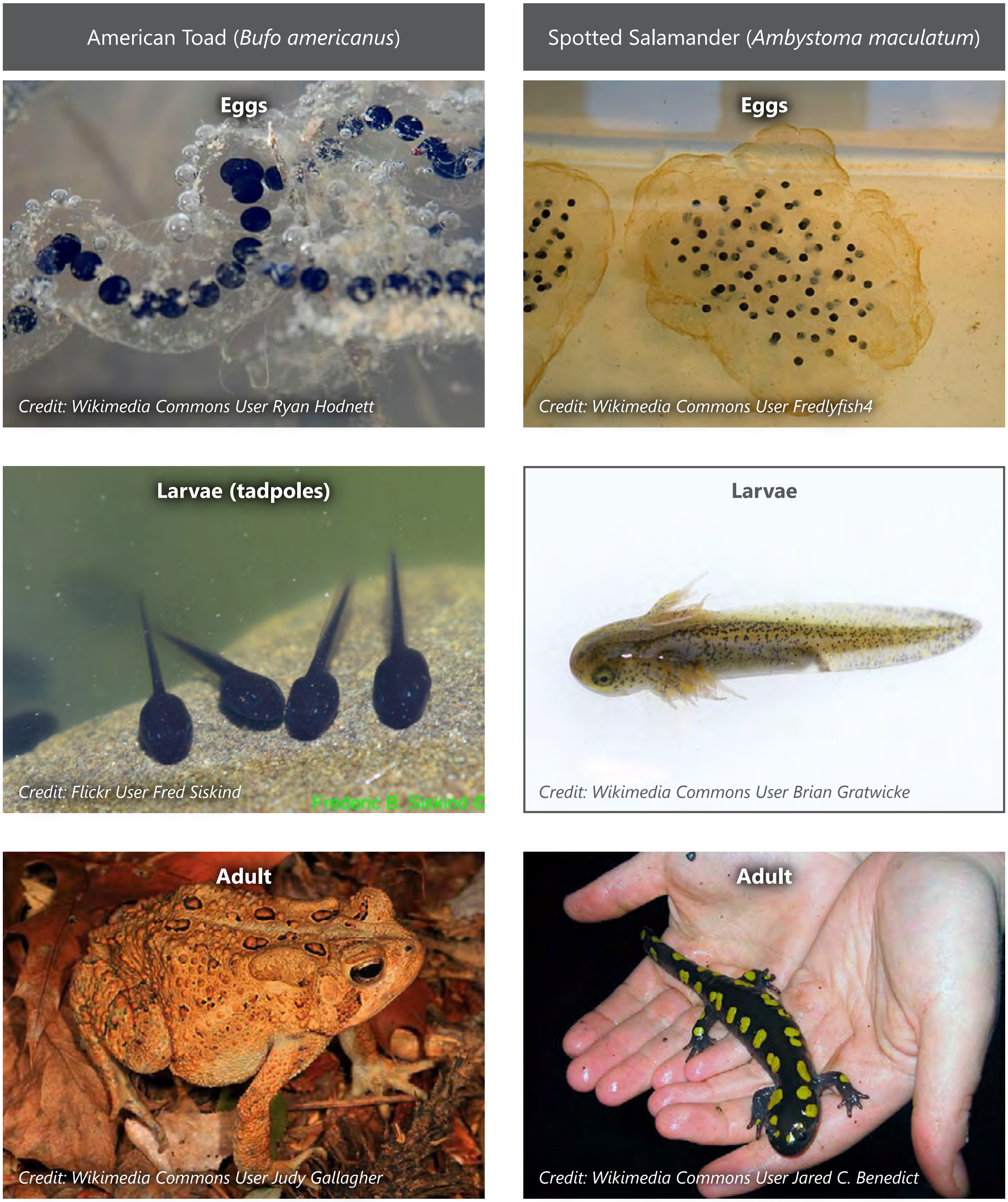
[417] *H.M. Wilbur, "Experimental Ecology of Food Webs: Complex Systems in Temporary Ponds,"* Ecology, *78:2,279-2,302, 1997.*

[418] *G.R. Ultsch, D.F. Bradford, and J. Freda, "Physiology: Coping with the Environment," pages 189-214 in: R.W. McDiarmid and R. Altig (editors),* Tadpoles: The Biology of Anuran Larvae, *University of Chicago Press, Chicago, Illinois, 1999.*

[419] *V.H. Shoemaker and K.A. Nagy, "Osmoregulation in Amphibians and Reptiles,"* Annual Review of Physiology, *39:449-471, 1977.*

[420] Ibid.

Figure 3.8
Life Stages of Two Amphibian Species



Source: Flickr and Wikimedia Commons

Figure 3.9
Some Wisconsin Amphibians

Wood Frog (*Lithobates sylvatica*)

Credit: Wikimedia Commons User Warren Bielenberg

Blue-Spotted Salamander (*Ambystoma laterale*)

Credit: Wikimedia Commons User Greg Schechter

Spring Peeper (*Lithobates crucifer*)

Credit: Wikimedia Commons User Peter Paplanus

Source: Wikimedia Commons

To maintain internal ion concentrations, amphibian kidneys produce large amounts of dilute urine at high rates.[421] This involves considerable reabsorption of chloride and sodium ions. Anurans typically reabsorb about 99 percent of the sodium ions from fluids passing through their kidneys.[422] While the rates of reabsorption are not as high in caudates, they have been reported as being in the range of 90 to 95 percent.[423]

The osmoregulatory mechanisms of amphibians are adapted to dilute freshwater environments. These mechanisms work to move ions into the amphibian body, keep them there, and to move water out of the body. Amphibians counteract higher external salinity by increasing their internal salinity through water

[421] *Ultsch et al. 1999,* op. cit.

[422] *H.O. Garland and I.W. Henderson, "Influence of Environmental Salinity on Renal and Adrenocortical Function in the Toad* Bufo marinus," General and Comparative Endocrinology, *27:136-143, 1975.*

[423] *L.B. Kirschner,T. Kerstetter, D. Porter, and R.H. Alvarado, "Adaptation of Larval* Ambystoma tigrinum *to Concentration Environments,"* American Journal of Physiology, *220:1,814-1,819, 1971; D.F. Stiffler and R.H. Alvarado, "Renal Function in Response to Reduced Osmotic Load in Larval Salamander,"* American Journal of Physiology, *266:1.243-1.249, 1974.*

loss.[424] While this can compensate for small increases in salinity, larger increases in external salinity can lead to dehydration and organ failure.

Amphibian egg membranes are also highly permeable and sensitive to osmotic changes.[425] As will be described below, increased salinity can lead to changes in developing eggs that reduce hatching success and promote deformities.

The breeding locations used by amphibians also make them sensitive to chloride salts and salinity. Most species breed in waterbodies or wetlands. The timing of breeding is typically triggered by water temperature. Some species start breeding in the early spring when considerable salt is likely to be present in the environment.[426] In Wisconsin for example, the breeding seasons of four species of frogs and five species of salamanders typically begin in late March.[427]

Amphibians potentially face high risk of exposure to contaminants like chloride due to their breeding and living part of their lives in waterbodies. Adults may potentially escape increases in salinity by dispersing to lower salinity environments or selecting more favorable oviposition sites,[428] but this might be limited by short dispersal ranges. For example, salamanders in the genus *Ambystoma* typically return to their natal pools to breed.[429] Similarly, most anurans have small migratory ranges compared to other vertebrates, often dispersing no more than 1,100 yards from their natal sites.[430] The limited dispersal ranges may not allow these organisms to move an adequate distance to escape impacts from chloride salts. Once eggs are laid, they are restricted to the aquatic environment in which they were laid and therefore cannot escape exposure to contaminants.[431] This restriction lasts until metamorphosis allows the young amphibians to enter the terrestrial environment.

The amount of time amphibians spend in water can affect the impacts they experience from chloride salts, with species that spend more time in water facing higher risk of exposure. This amount of time differs among species.[432] Larval wood frogs (*Lithobates sylvatica)* are typically in ponds for about five to nine weeks. Similarly, larval spotted salamanders (*Ambystoma maculatum*) spend 13 to 18 weeks in ponds. Green frog (*Rana clamitans*) larvae, on the other hand, spend over a year in ponds. Amphibian species also differ in the amount of time adults spend in water. Adult wood frogs and spotted salamanders live in terrestrial habitats, and only spend a few weeks during the breeding season in water. While adult green frogs may disperse over land, they spend most of their adult lives in water.

Utilization of certain habitats may pose additional risks of exposure to amphibians. For example, some amphibian species breed in ephemeral ponds that are created by snowmelt and spring rains. These pools lack inlets and outlets and may or may not be hydraulically connected to groundwater. They are desirable breeding sites for amphibians because they lack fish, which are major predators of amphibian eggs and

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[424] *J.B. Baliniski, "Adaptation of Nitrogen Metabolism to Hyperosmotic Environments in Amphibia,"* The Journal of Experimental Zoology*, 215:335-350, 1981.*

[425] *F.R. Hunter and O. De Luque, "Osmotic Studies of Amphibian Eggs. II. Ovarian Eggs,"* Biological Bulletin*, 117:468-481, 1959.*

[426] *Collins and Russell 2009,* op. cit*.*

[427] *R. Christoffel, R. Hay, and M. Wolfgram,* Amphibians of Wisconsin*, Wisconsin Department of Natural Resources PUB-ER-105-2001, 2001.*

[428] *B. Viertel, "Salt Tolerance of* Rana temporaria*: Spawning Site Selection and Survival During Embryonic Development (Amphibia, Anura),"* Amphibia-Reptilia*, 20:161-171, 1999.*

[429] *C.R. Shoop, "Orientation of* Ambystoma maculatum*: Movements Near Breeding Ponds and Displacements of Migrating Individuals,"* Biological Bulletin*, 135:230-238, 1968; S.L. Stenhouse, "Migratory Orientation and Homing in* Ambystoma maculatum *and* Ambystoma opacum*,"* Copeia*, 1985:631-637, 1985.*

[430] *U. Sinsch, "Migration and Orientation in Anuran Amphibians,"* Ethology, Ecology & Evolution*, 2:65-79, 1990.*

[431] *K. Chinathamby, R.D. Reina, P.C.E. Bailey, and B.K. Lees, "Effects of Salinity on the Survival, Growth and Development of Tadpoles of the Brown Tree Frog,* Litoria ewingii*,"* Australian Journal of Zoology*, 54:97-105, 2006.*

[432] *N.E. Karraker, "Are Embryonic and Larval Green Frogs (*Rana clamitans*) Insensitive to Road Deicing Salt?"* Herpetological Conservation and Biology*, 2:35-41, 2007.*

larvae. Contaminants can enter these temporary waterbodies through overland flow. The concentrations of these substances may increase as water evaporates. Constructed stormwater retention ponds also serve as habitats for many amphibian species.[433] These ponds may have high concentrations of chloride due to runoff from roads and other impervious surfaces.[434] Chemical stratification can occur in retention ponds, with salt concentrations near the bottom being two to five times higher than that at the surface.[435] This can pose special risks to amphibian species such as spring peepers (*Pseudacris crucifer*) that deposit their eggs at the bottom.[436]

Types of Effects of Chloride Salts and Salinity on Amphibians

Exposure to chloride, chloride salts, or salinity has been found to cause a variety of sublethal effects in amphibians. While different effects have been observed in different species, these effects fall into four broad categories: changes in behavior, changes in growth and development, impacts on reproduction, and increases in levels of stress hormones. It is also important to recognize that relatively few species have been examined and most of those are species that are easily reared or kept in a laboratory or mesocosm setting. In addition, most of the research has been conducted on amphibian eggs, embryos, and larvae. Much less work has examined impacts of chloride salts on adult amphibians.

Impacts of Chloride Salts and Salinity on Amphibian Behavior

Increases in the concentrations of chloride salts and salinity can lead to changes in amphibian behavior. Examples of this include salinity affecting amphibian activity levels, the amount of anti-parasite behavior amphibians display, and the choice of amphibian breeding locations.

Studies have reported reductions in general activity levels of larvae in several amphibian species with increasing chloride concentration or salinity.[437] Tadpoles of the frog *Rana temporaria* exposed to sodium chloride over periods of 42 and 56 days showed reductions in the amount of movement and the speed at which they moved with increasing chloride concentration.[438] At high sodium chloride concentrations, the tadpoles also moved shorter distances than at low concentrations. Less effect was seen over 14- and 28-day exposures. Similarly, the activity levels in larvae of American toad (*Anaxyrus americanus*) exposed to sodium chloride at a concentration 780 mg/l were reduced by 13 percent.[439] Wood frog (*Lithobates sylvatica*) larvae exposed to sodium chloride also showed lower activity levels.[440] At higher chloride concentrations the larvae also swam in tight circles. By inducing these sorts of behavioral changes, chloride salts and salinity may lower the foraging and predator avoidance abilities of amphibian larvae, leading to increased mortality.[441]

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[433] *J.W. Snodgrass, J. Simon, and R. Casey, "Ecotoxicology of Amphibians and Reptiles in Urban Environments," Chapter 12, pages 177-196, In: J.C. Mitchell and R.E. Jung Brown (editors),* Urban Herpetology, *Society for the Study of Amphibians and Reptiles, Salt Lake City, Utah, 2008; E.C. Ostergaard, K.O. Richter, and S.D. West, "Amphibian Use of Stormwater Ponds in the Puget Sound Lowlands of Washington, Chapter 17, pages 259-270, In: J.C. Mitchell and R.E. Jung Brown (editors),* Urban Herpetology, *Society for the Study of Amphibians and Reptiles, Salt Lake City, Utah, 2008.*

[434] *N.E. Karraker, "Impacts of Road Deicing Salts on Amphibians and Their Habitats," Chapter 14, pages, 183-196, In: J.C. Mitchell and R.E. Jung Brown (editors),* Urban Herpetology, *Society for the Study of Amphibians and Reptiles, Salt Lake City, Utah, 2008.*

[435] *P.M. Marsalek, W.E. Watts, J. Marsalek, and B.C. Anderson, "Winter Flow Dynamics of an On-Stream Stormwater Management Pond,"* Water Quality Research Journal of Canada, *35:505-523, 2000.*

[436] *E.K. Dobbs, M.G. Brown, J.W. Snodgrass, and D.R. Ownby, " Salt Toxicity to Treefrogs (*Hyla chrysoscelis*) Depends on Depth,"* Herpetologica*, 68:22-30, 2012.*

[437] *Collins and Russell 2009,* op. cit.

[438] *M. Denoël, M. Bichot, G.F. Ficetola, J. Delcourt, M. Ylieff, P. Kestermant, and P. Poncin, "Cumulative Effects of Road Deicign Salt on Amphibian Behavior,"* Aquatic Toxicology, *99:275-280, 2010.*

[439] *D.K. Jones, B.M. Mattes, W.D. Hintz, M.S. Schuler, A.B. Stoler, L.A. Lind, R.O. Cooper, and R.A. Relyea, "Investigations of Road Salts and Biotic Stressors on Freshwater Wetland Communities,"* Environmental Pollution*, 221:159-167, 2017.*

[440] *D. Sanzo and S.J. Hecnar, "Effects of Road Deicing Salts on Larval Wood Frogs (*Rana sylvatica*),"* Environmental Pollution*, 140:247-256, 2006.*

[441] *Karraker 2008, op. cit.; C. Teplitsky, S., Plenet, J.-P., Léna, N., Mermet, E. Malet, and P. Joly, P., "Escape Behaviour and Ultimate Causes of Specific Induced Defences in an Anuran Tadpole," Journal of Evolutionary Biology, 18:180–190, 2005.*

Exposure to chloride salts can also affect behaviors that reduce the likelihood that amphibian larvae will become infected with parasites. In one experiment, wood frog (*Lithobates sylvatica*) tadpoles were exposed to three concentrations of road salt consisting mostly of sodium chloride.[442] Higher intensities of infection with trematode flukes were seen at sodium chloride concentrations of 400 mg/l and 800 mg/l than at 160 mg/l. This correlated with the amount of anti-parasite behavior observed in the tadpoles. Less anti-parasite behavior occurred at the two higher concentrations than at the lowest one.

Concentrations of chloride salts and salinity can affect the choice of breeding locations by amphibians. This is important because the distribution of amphibians depends on their ability to locate suitable sites for egg laying and the ability of embryos and larvae to survive, develop, and undergo metamorphosis at these sites.[443] Some amphibian species choose breeding and egg laying sites based partly on salinity.[444] A field study in Nova Scotia, Canada found significant differences in the chloride concentrations of ponds occupied and not occupied by spotted salamanders (*Ambystoma maculatum*) and spring peepers (*Pseudacris crucifer*), with ponds that had higher chloride concentrations being unoccupied.[445] A second field study found wood frogs (*Lithobates sylvatica*) and spring peepers calling only in wetlands with chloride concentrations below 250 mg/l.[446] A third study found that wood frogs did not breed in stormwater ponds with chloride concentrations above 260 mg/l, whereas American toads (*Anaxyrus americanus*) were found breeding in these stormwater ponds.[447] Given the short dispersal ranges of many amphibian species, contamination of ponds with chloride could restrict breeding opportunities.

Impacts of Chloride Salts and Salinity on Amphibian Growth and Development

Exposure to chloride salts and salinity can affect the growth and development of amphibians. Three main effects have been reported: slower growth of larvae that leads to them requiring a longer period to reach metamorphosis, smaller size and lower weight at metamorphosis, and impacts on sex determination and alteration of sex ratios.

Exposure of amphibian eggs and larvae to chloride salts and salinity can lead to slower growth and extend the time needed for larvae to reach metamorphosis. For example, spotted salamander (*Ambystoma maculatum*) larvae in reciprocal transplants of egg masses between pools unimpacted and impacted with chloride grew more slowly in impacted pools than in unimpacted pools, regardless of the type of pool from which they originated.[448] In laboratory experiments, spotted salamander larvae grown at a chloride concentration of 8 mg/l required 34 days to reach metamorphosis, while those grown at a chloride concentration of 900 mg/l required 74 days.[449] Similar effects have been reported in gulf coast toad (*Incilius vallaiceps*),[450] natterjack toad (*Bufo calamita*),[451] and brown tree frog (*Litoria ewingii*).[452] Interestingly, metamorphosis occurred earlier in wood frogs (*Lithobates sylvatica*) that were exposed to

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[442] *D. Milotic, M. Milotic, and J. Koprivnikar, "Effects of Road Salt on Larval Amphibian Susceptibility to Parasitism through Behavior and Immunocompetence,"* Aquatic Toxicology*, 189:42-49, 2017.*

[443] *L.G. Alexander, S.P. Lailvaux, J.H.K. Pechmann, and P.J. DeVries, "Effects of Salinity on Early Life Stages of the Gulf Coast Toad* Incilius nebulifer *(Anura: Bufonidae),"* Copeia*, 2012:106-114, 2012.*

[444] *T. Haramura, "Salinity Tolerance of Eggs of* Buergeria japonica *(Amphibia, Anura) Inhabiting Coastal Areas,"* Zoological Science*, 24:820-823, 2007.*

[445] *Collins and Russell 2009,* op. cit.

[446] *E. Sadowski, "The Impact of Chloride Concentrations on Wetlands and Amphibian Distributions in the Toronto Region,"* Prairie Perspectives*, 5:144-162, 2002.*

[447] *M.T. Gallagher, J.W. Snodgrass, A.B. Brand, R.E. Casey, S.M. Lev, and R.J. Van Meter, "The Role of Pollutant Accumulation in Determining the Use of Stormwater Ponds by Amphibians,"* Wetlands Ecology and Management*, 22:551-564, 2014.*

[448] *S.P. Brady, "Road to Evolution? Local Adaptation to Road Adjacency in an Amphibian (*Ambystoma maculatum*),"* Scientific Reports*, 2:235, doi: 10.1038/srep00235, 2012.*

[449] *Collins 2010,* op. cit.

[450] *Alexander et al. 2012,* op. cit.

[451] *I. Gomez-Mestre, M. Tejedo, E. Demayo, and J. Estepa, "Developmental Alterations and Osmoregulatory Physiology of a Larval Anuran under Osmotic Stress,"* Physiological and Biochemical Zoology*, 77:267-274, 2004.*

[452] *Chinathamby et al. 2006,* op. cit.

higher concentrations of sodium chloride, but the weight of the new adults was lower than those grown at lower concentrations.[453]

Slower growth of amphibian larvae and delays reaching metamorphosis can lead to fewer adults entering amphibian populations. First, a longer larval period exposes the organisms to higher risk of predation. Many predators of amphibian larvae are gape limited—the size of the prey that they can eat is limited by the size of their mouths. Because of this, smaller larvae are more likely to be eaten. In fact, at least one study has shown that some predators of anuran larvae prefer smaller tadpoles as prey.[454] As a result, being smaller for a longer time increases their risk of being predated.[455] Second, some amphibians lay their eggs in ephemeral ponds. These species need to complete larval development and metamorphose before the ponds dry out. Longer development periods induced by chloride salts could result in the larval habitat disappearing before these amphibians have reached metamorphosis.[456]

Exposure to chloride salts and salinity can result in amphibian larvae being smaller and having lower weight at metamorphosis. Spotted salamander (*Ambystoma maculatum*) larvae in reciprocal transplants of egg masses between pools unimpacted and impacted with chloride were 11.3 percent smaller in impacted pools than in unimpacted pools, regardless of the type of pool from which they originated.[457] A second study found that spotted salamander larvae reared in media with higher concentrations of chloride had lower weight at metamorphosis.[458] Similarly, the weight of newly metamorphosized gulf coast toads (*Incilius vallaiceps)* decreased with the salinity that their eggs and tadpoles were reared in.[459] The reduction in size at metamorphosis can have impacts on both individual amphibians and amphibian populations. Size at metamorphosis is a major factor influencing survival and fitness of juvenile and adult amphibians.[460] Smaller amphibian individuals have less resistance to dehydration than larger ones because they have greater surface area to volume ratios. Small size increases the relative amount of surface area over which evaporation of water from their bodies can occur, potentially increasing evaporation. In addition, smaller size at metamorphosis can lead to less egg production, both through smaller individuals beginning to reproduce at an older age and smaller individuals producing fewer eggs.

Exposure to chloride salts can also affect sex determination in some amphibians. A mesocosm study found that exposure of wood frog (*Lithobates sylvatica*) larvae to chloride concentrations of 867 mg/l reduced the female to male sex ratio in the frogs by 10 percent in comparison to controls.[461] The fact that sex ratios in mesocosms were not correlated with survivorship indicates that this effect is likely due to the masculinization of frogs and not due to sex-based mortality.

Impacts of Chloride Salts and Salinity on Amphibian Reproduction

Chloride salts and salinity can affect amphibian reproduction. Examples of impacts include reducing egg production, interfering with egg physiology and survival, reducing egg hatching success, and interfering with early development leading to deformities and abnormalities in larvae.

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[453] *Sanzo and Hecnar 2006,* op. cit.

[454] *L. Richards and C.M. Bulls, "Size Limited Predation on Tadpoles of Three Australian Frogs,"* Copeia*, 1990:1,041-1,046, 1990.*

[455] *Chinathamby et al. 2006,* op. cit.

[456] *Collins 2010,* op. cit.

[457] *S.P. Brady, 2012,* op. cit.

[458] *Collins 2010,* op. cit.

[459] *Alexander et al. 2012,* op. cit.

[460] *D.C. Smith, "Adult Recruitment in Chorus Frogs: Effects of Size and Date at Metamorphosis,"* Ecology*, 68:344-350, 1987; R.D. Semlitsch, D.E. Scott, and J.H.K. Pechmann, "Time and Size at Metamorphosis Related to Adult Fitness in* Ambystoma talpoideum*,"* Ecology*, 69:184-192, 1988.*

[461] *M.R. Lambert, A.B. Stoler, M.S. Smylie, R.A. Relyea, and D.K. Skelly, "Interactive Effects of Road Salt and Leaf Litter on Wood Frog Sex Ratios and Sexual Size Dimorphism,"* Canadian Journal of Fisheries and Aquatic Life*, 74:141-146, 2016.*

Exposure to chloride salts can lead to reduced egg production in amphibians. One study found that egg masses of spotted salamander (*Ambystoma maculatum*) in roadside pools with higher specific conductance and chloride concentrations contained about 30 percent fewer eggs than those in woodland pools with lower specific conductance and chloride concentrations.[462] Chloride may only produce this impact in some amphibian species. The authors noted that that no difference was seen between the number of eggs in wood frog (*Lithobates sylvatica*) egg masses in the two pool types.

Exposure to chloride salts and salinity can also affect the physiology and survival of amphibian eggs. After amphibian egg masses are laid, their size increases due to water uptake. The size increase can be quite dramatic. For example, the size of spotted salamander (*Ambystoma maculatum*) egg masses can increase by a factor of four due to water uptake.[463] This water uptake provides several benefits to the eggs. It improves respiration within the clutch;[464] decreases the risk of disease to individual eggs;[465] and protects eggs against ultraviolet light,[466] desiccation,[467] and predation.[468]

In one study examining the impact of chloride and salinity on egg expansion, newly laid egg masses of spotted salamanders (*Ambystoma maculatum*) were incubated for nine days in solutions with three different chloride concentrations.[469] Following this incubation, all the egg masses were transferred to the solution with the lowest concentration of chloride for eight days. During the first phase of the experiment, the weight of egg masses incubated at a chloride concentration of 1 mg/l increased by 27 percent. Those eggs masses incubated in solutions with chloride concentrations of 145 mg/l and 945 mg/l lost 18 percent and 33 percent, respectively, of their original weight. After being transferred into a 1 mg/l chloride solution, the egg masses originally incubated at the lowest chloride concentration (1 mg/l) lost 2 percent of their original weight. Those that were originally incubated at the intermediate concentration gained 15 percent of their original weight, while those originally incubated at the highest chloride concentration lost another 10 percent of their original weight. The results of this experiment suggest that exposure to high enough concentrations of chloride salts and salinity can cause permanent damage to amphibian eggs through disruption of their osmoregulatory ability. When egg masses are exposed to relatively low concentrations of chloride, they remain able to take up water when the solution they are in becomes more dilute. In nature, it means that when spring rains lower chloride concentrations in ponds, water losses from egg masses caused by salinity may be reversed. But there is a limit to this ability. When the concentration of chloride becomes too high, the egg masses lose this capacity and spring rains may not be adequate to reverse the water loss caused by elevated chloride concentration.

Elevated salinity and concentrations of chloride salts can also induce production of deformed embryos in developing amphibian eggs. The mechanisms are similar to those that produce deformities in fish embryos—higher salinity causes shrinkage of the perivitelline space in the egg decreasing the volume in which the embryo has to develop leading to the induction of deformities[470] (see the section on effects on fish). Several types of deformities have been reported. Wood frog (*Lithobates sylvatica*) eggs and larvae exposed to sodium chloride concentrations between 0 mg/l and 750 mg/l until they underwent

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[462] *N.E. Karraker and J.P. Gibbs, "Contrasting Road Effect Signals in Reproduction of Long- Versus Short-Lived Amphibians,"* Hydrobiologia*, 664:213-218, 2011.*

[463] *N.E. Karraker and J.P. Gibbs, "Road Deicing Salt Irreversibly Disrupts Osmoregulation of Salamander Egg Clutches,"* Environmental Pollution*, 159:833-835, 2011.*

[464] *Karraker 2008,* op. cit.

[465] Ibid.

[466] *K.P. Grant and L.E. Licht, "Effects of Ultraviolet Radiation on Life-History Stages of Anurans from Ontario, Canada,"* Canadian Journal of Zoology*, 73:2,292-2,301, 1995.*

[467] *W.E. Duellman, and L. Trueb,* Biology of Amphibians*, John Hopkins University Press, Baltimore, Maryland, 1986.*

[468] *S.C. Richter, "Larval Caddisfly Predation on the Eggs and Embryos of* Rana capito *and* Rana sphenocephala," Journal of Herpetology*, 34:590-593, 2000.*

[469] *Karraker and Gibbs 2011* Environmental Pollution*, op. cit.*

[470] *A.D. Padhye and H.J. Ghate, "Sodium Chloride and Potassium Chloride Tolerance of Different Stages of the Frog,* Microhyla ornate,' Herpetological Journal*, 2:18-23, 1992.*

metamorphosis at 100 days showed deformities at higher salt concentrations.[471] These deformities included bent tails, scoliosis, missing forelimbs, elongated rear limbs, and missing portions of their lower jaws. Swelling from abdominal edema was common at higher concentrations. This edema indicates that the frogs were undergoing kidney failure. The percentage of rough-skinned newts (*Taricha granulosa*) embryos hatching with deformities increased with increasing concentration of chloride in the medium in which they were incubated.[472] In control solutions, about 6 percent of embryos showed deformities. This percentage rose to about 74 percent at a chloride concentration of 2,000 mg/l with sodium chloride and 61 percent at the same chloride concentration with magnesium chloride. In these experiments, higher salt concentration led to more severe deformities. Increases in deformities at relatively high values of specific conductance have also been reported in green frogs (*Rana clamitans*).[473]

Impacts of Chloride Salts and Salinity on Amphibian Stress Hormones

High levels of exposure to sodium chloride can increase levels of amphibian stress hormones such as corticosterone.[474] This can lower the ability of amphibians to produce a normal immune response and can reduce larval growth by increasing the development rate.[475] Hormone changes can also alter the behavior of larval amphibians.[476]

<u>Amphibian Ability to Adapt to Higher Salinity</u>

It should be noted that some amphibians have demonstrated adaptation to increased salinity.[477] Examples of this come mostly from coastal amphibian populations and probably developed over many generations.[478]

Reptiles

Turtles are the only group of reptiles in Wisconsin that live in aquatic habitats. Unlike other reptiles, turtles have shells that are fused to their backbones and ribs. Turtles are long-lived and slow to mature. Blanding's turtle (*Emydoidea blandingii*), for example, may live for over 80 years and females can take 17 to 20 years to reach sexual maturity.[479] Turtles also have long generation times, low survival of eggs and hatchlings, high adult survival, and low mobility.[480]

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[471] *M.L. Harless,* Effects of Chemical Deicers on Amphibian Communities*, Ph.D. Dissertation, Michigan Technological University, Houghton, Michigan, 2012.*

[472] *G.R. Hopkins, S.S. French, and E.M. Brodie, Jr., "Increased Frequency and Severity of Developmental Deformities in Rough-Skinned Newt (*Taricha granulosa*) Embryos Exposed to Road Deicing Salts (NaCl & $MgCl_2$),"* Environmental Pollution*, 173:264-269, 2013.*

[473] *N.E. Karraker, "Are Embryonic and Larval Green Frogs (*Rana clamitans*) Insensitive to Road Deicing Salts?"* Herpetological Conservation and Biology, *2:35-41, 2007.*

[474] *M.F. Bennett and A.O. Johnson, "Osmotic Stress ACTH and the White Blood Cell Picture in Newts,* Notophthalamus viridescens," Journal of Comparative Physiology, *82:333-338, 1973.*

[475] *A. Tournefier, "Corticosteroid Action of Lymphocyte Subpopulations and Humoral Immune Responses of Axolotl (Urodele Amphibian),"* Immunology, *45:155-162,1982; B.E. LaFonte and P.T.J. Johnson, "Experimental Infection Dynamics: Using Immunosuppression and In Vivo Parasite Tracking to Understand Host Resistance in an Amphibian-Trematode System,"* Journal of Experimental Biology, *216: 3,700-3,708, 2013.*

[476] *M.E. Fraker, F. Hu, V. Chuddapah, S.A. McCollum, R.A. Relyea, J. Hempel, and R.J. Denver, "Characterization of an Alarm Pheromone Secreted by Amphibian Tadpoles that Induces Behavioral Inhibition and Suppression of the Neuroendocrine Stress Axis,"* Hormones and Behavior, *55:520-529, 2009.*

[477] *T.J.C. Beebee, "Salt Tolerance of Natterjack Toad (*Bufo calamita*) Eggs and Larvae from Coastal and Inland Populations in Britain,"* Herpetological Journal*, 1:14-16, 1985; I. Gomez-Mestre, and M. Tejedo, "Contrasting Patterns of Quantitative and Neutral Variation in Locally Adapted Populations of the Natterjack Toad,* Bufo calamita," Evolution*, 58:2,343-2,352, 2004.*

[478] *Karraker 2008,* op. cit.

[479] *R. Christoffel, R. Hays, and M. Monroe,* Turtles & Lizards of Wisconsin, *Wisconsin Department of Natural Resources PUB-ER-104 2002, 2002.*

[480] *J.P. Vanek and G.A. Glowacki, "Assessing the Impacts of Urbanization on Sex Ratios of Painted Turtles (*Chrysemys picta*),"* Diversity, *11:72, doi: 10.3390/d11050072, 2019.*

Eleven species of turtles live in Wisconsin. Four of these species are shown in Figure 3.10. The habitats they use vary among species, although most species are aquatic. Two species, Blanding's turtle and wood turtle (*Clemmys insculpta*) are semi-terrestrial, meaning they move between land and water. One species, the ornate box turtle (*Terrapene ornata*) is fully terrestrial. Regardless of the habitat used by adults, all turtles lay their eggs on land. Most turtle species do this in self-excavated nests, though common musk turtles (*Sternotherus odoratus*) will sometimes lay their eggs on bare ground or in shallow depressions under logs or rocks.

Turtles perform several roles in aquatic and terrestrial communities. Many species are omnivorous, eating plants as well as living and freshly dead animals. The diets of some turtle species change as they age. For example, juvenile painted turtles (*Chrysemys picta*)[481] feed heavily on insects. As painted turtles mature, their diet shifts to herbivory.[482] Where turtles feed is based on the habitats that they use. Aquatic species feed only in water, though common snapping turtles (*Chelydra serpentina*) may occasionally pull some prey into water edge. Terrestrial turtle species feed only on land while semi-terrestrial species feed in both water and on land.

Turtle eggs, hatchlings, and juveniles serve as prey for other animals. These include birds such as crows, ravens, and herons; fish such as bass and pike; and mammals such as mink, raccoons, skunks, and coyotes. Turtles are also preyed upon by free-ranging house cats. Eggs and hatchlings are heavily preyed upon. Only about five to 10 percent of turtle eggs survive to hatch and only one to three percent of hatchlings survive to adulthood.[483]

<u>Factors Affecting Turtle Sensitivity to Chloride Salts and Salinity</u>

Some general features of the biology of turtles can make them sensitive to impacts from chloride salts and salinity in general. Some species dwell primarily at the bottom of waterbodies. In addition, all Wisconsin turtles except the ornate box turtle spend winter under water. In some species, individuals bury themselves in the substrate while individuals in other species lie on top of the substrate during winter. Because of the effects of salt on water's density (see Chapter 2 of this report), these behaviors may expose turtles to levels of chloride and salinity higher than the average in the water column. Turtles that excavate nests in soils near roads may also expose their eggs to higher concentrations of salinity and chloride.

<u>Impacts of Chloride Salts and Salinity on Freshwater Turtles</u>

The impacts of chloride salts and salinity on freshwater turtles have been poorly studied. The available studies examine only a few species. In addition, the emphasis in most research has been on turtle species living in marine coastal areas that use estuaries as habitats or that may be impacted by sea level rise due to climate change. These studies have often examined the impacts of chloride concentrations and salinities typical of brackish water systems and seawater, which can be even higher than those found in contaminated inland waters. Less research has examined impacts on inland species or salinity and chloride concentrations more typical of contaminated inland waters.

High salinity has been found to produce physiological effects in turtles. Many species lose body mass when exposed to saline conditions, presumably from water loss.[484] At salinities over 17,500 mg/l, this may be accompanied by rapid water loss, decreased muscle moisture, and increased levels of plasma electrolytes.[485] Extended exposure to high salinity can lead to dehydration.[486] Net water loss in turtles due to salinity is inversely proportional to body size.[487] This provides larger turtles greater tolerance to salinity than smaller turtles.

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[481] *Wisconsin is home to two subspecies of painted turtles: the western painted turtle (*Chrysemys picta belli*) and the midland painted turtle (*Chrysemys picta marginata*). Both subspecies are found throughout the State.*

[482] *Christoffel et al. 2002,* op. cit.

[483] Ibid.

[484] *P.J. Bentley, W.L. Bretz, and K. Schmidt-Nielsen, "Osmoregulation in the Diamondback Terrapin* Malaclemys terrapin centrata," Journal of Experimental Biology*, 46:161-1678, 1967; W.A. Dunson and M.E. Seidel, "Salinity Tolerance of Estuarine and Insular Emydid Turtles (*Pseudemys nelson *and* Trachemys decussata*),"* Journal of Herpetology*, 20:237-245, 1986.*

[485] *M. Agha, J.R. Ennen, D.S. Bower, A.J. Nowakowski, S.C. Sweat, and B.D. Todd, "Salinity Tolerances and Use of Saline Environments by Freshwater Turtles: Implications of Sea Level Rise,"* Biological Reviews*, 93:1,634-1,648, 2018.*

[486] *D.S. Bower, C.E. Death, and A. Georges, "Ecological and Physiological Impacts of Salinization on Freshwater Turtles of the Lower Murray River,"* Wildlife Research*, 39:705-710, 2012.*

[487] *W.A. Dunson, "Estuarine Populations of the Snapping Turtle* (Chelydra*) as a Model for the Evolution of Marine Adaptations in Reptiles,"* Copeia*, 1986:741-756, 1986.*

Figure 3.10
Some Wisconsin Turtles

Snapping Turtle (*Chelydra serpentina*)


Credit: Joseph Boxhorn, SEWRPC

Common Musk Turtle (*Sternotherus odoratus*)


Credit: Wikimedia Commons User Ontley

Blanding's Turtle (*Emydoidea blandingii*)


Credit: Gregor Schuurman, WDNR

Painted Turtle (*Chrysemys picta*)


Credit: Joseph Boxhorn, SEWRPC

Source: Wikimedia Commons, WDNR, and SEWRPC

Salinity can also affect reproduction in turtles. One experiment incubated eggs of broad-shelled snake-necked turtles (*Chelodina expansa*) in media consisting of one-to-one mixtures of vermiculite and water.[488] Treatments consisted of differences in the salinity of the water. Eggs incubated in mixtures with higher salinities had 39 percent less survival than those incubated in freshwater. In addition, hatchlings emerging from eggs in saline treatments were smaller and had higher plasma concentrations of sodium, chloride, and urea than those incubated in freshwater. The size difference is important because larger hatchlings survive longer, grow faster, and move more quickly than smaller ones. At hatching the residual yolk sac was larger in hatchlings incubated at higher salinities. This indicated that less yolk was used during growth and may reflect lower absorption of water by the eggs during incubation.[489]

[488] *D.S. Bower, K.M. Hodges, and A. Georges, "Salinity of Incubation Media Influence Embryonic Development of a Freshwater Turtle,"* Journal of Comparative Physiology B*, 183:235-241, 2013.*

[489] *D. Booth, "Incubation of Rigid-Shelled Turtle Eggs: Do Hydric Conditions Matter?"* Journal of Comparative Physiology B*, 172:627-633, 2002.*

Water exchange between turtle eggs and the environment during incubation is a major factor determining hatchling characteristics. Water exchange is influenced by the salinity of the soil surrounding the nest, with more saline soil leading to less exchange. The amount of exchange can affect several turtle egg characteristics including the amount of time the eggs take to hatch,[490] the sex of the hatchlings,[491] and the size of the hatchlings.[492]

Mechanisms That Allow Freshwater Turtles to Cope with Chloride Salts and Salinity

Some freshwater turtle species have means for coping with increased concentrations of chloride salts and salinity. These include both physiological and behavioral mechanisms. Physiologically, many freshwater turtles regulate osmotic pressure from salinity by increasing the concentration of urea in their plasma.[493] This decreases the rate at which these turtles lose water to the environment.[494] In addition, some turtles can accumulate high concentrations of salts in their bladder fluids and excrete these salts with urea.[495]

Flexible behavior also allows some turtle species to temporarily occupy environments with high salinity, including brackish water environments.[496] At least three types of behaviors are seen that confer some tolerance to salinity. First, some turtle species may move frequently between saline and freshwater areas allowing them to use the saline environments. For example, common snapping turtles (*Chelydra serpentina*) cannot survive prolonged exposure to salinities of about 14,000 mg/l but are able to persist in estuarine habitats through periodic access to freshwater during low tide.[497] This behavior requires that there be freshwater refuges available for these turtles to use. Second, turtles can reduce feeding and drinking that result in the ingestion of high salinity water.[498] This reduction can cause large increases urea in internal fluids, which cannot be maintained indefinitely without access to fresh water.[499] Third, some turtles will drink fresh water that is floating on top of more saline water in the environment.[500]

Effects on Terrestrial Organisms

The presence of chloride salts in the environment can also impact terrestrial organisms. In general, this has not been as well-studied as the impacts on aquatic organisms. While considerable information is available on impacts of chloride salts on terrestrial plants, less information is available on other terrestrial organisms. This section reviews the impacts of chloride salts on terrestrial plants and vertebrates such as birds and mammals.

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[490] *M. Charnier, "Action de la Temperature sur la Sex-Ration Chez L'embryon d'*Agama agama *(Agamidae, Lacertilien),"* Societe de Biologie de l'Ouest Africain, *160:620-622, 1966 cited in* Bower *et al. 2013,* op. cit.

[491] *C.L. Yntema, "Times for Eggs of the Turtle* Cheldra Serpentina *(Testundines: Chelydridae) at Various Temperatures,"* Herpetologica*, 34:227-274, 1978.*

[492] *M.S. Finkler, "Influence of Water Availability During Incubation on Hatchling Size, Body Composition, Desiccation Tolerance, and Terrestrial Locomotor Performance in the Snapping Turtle* Chelydra serpentina," Physiological and Biochemical Zoology, *72714-722, 1999.*

[493] *M. Gilles-Baillien, "Urea and Osmoregulation in the Diamondback Terrapin* Malaclemys centrata centrata*, (Latreille),"* Journal of Experimental Biology*, 52:691-697, 1970.*

[494] *S.M.L. Lee, W.P. Wong, A.M. Loong, KC. Hiong, F.C. Shit, and K.I Yuen, "Postprandial Increases in Nitrogen Excretion and Urea Synthesis in the Chinese Soft-Shelled Turtle,* Pelodiscus sinensis," Journal of Comparative Physiology B, *177:19-29, 2006.*

[495] *M. Gilles-Baillien, "Hibernation and Osmoregulation in the Diamondback Terrapin* Malaclemys centrata centrata*, (Latreille),"* Journal of Experimental Biology, *59:45-51, 1973.*

[496] *R. Greenberg and J.E. Maldonado, "Diversity and Endemism in Tidal-Marsh Vertebrates,"* Studies in Avian Biology*, 32-53, 2006.*

[497] *J.J. Kinneary, "Salinity Relations of* Chelydra serpentina *in a Long Island Estuary,"* Journal of Herpetology, *27:441-446, 1993.*

[498] *Bower et al. 2012,* op. cit.

[499] *J. Davenport and J.F Ward, "The Effects of Salinity and Temperature on Appetite in the Diamondback Terrapin* Malaclemys terrapin *(Latreille),"* The Herpetological Journal*, 3:95-98, 1993.*

[500] *W.A. Dunson, "Effect of Water Salinity and Food Salt Content on Growth and Sodium Efflux of Hatchling Diamondback Terrapins (*Malaclemys*),"* Physiological Zoology, *58:736-747, 1985.*

Plants

Terrestrial plants include both mosses and vascular plants that live on land. These form integral parts of terrestrial food webs, converting carbon dioxide and inorganic nutrients present in the air and soil into organic compounds that are directly available as food for other organisms. This process, known as photosynthesis, uses energy from sunlight to create carbohydrates and releases oxygen required by other organisms. Plants serve as the base of the food web, providing food for animals. They also provide habitat for other organisms. In addition, plants provide food, fibers, and building materials for humans.

Roles of Chloride Salts in Plant Nutrition

Chloride is a necessary micronutrient for plants. Adequate tissue concentrations are about 100 mg of chloride per kilogram of plant dry mass (mg/kg).[501] The amount of chloride needed for plant and crop growth can generally be supplied by rainfall.[502] Chloride deficient plants are rarely seen in nature or agriculture. Chloride is a major osmotically active solute in the vacuoles of plant cells.[503] It is involved in turgor regulation and osmoregulation. Chloride regulates the activities of some enzymes in the cytoplasm of plant cells. It is also involved in the expansion of leaves and elongation of leaf, shoot, and root cells, processes that are important in plant growth.[504] While plants require small amount of chloride, excessive levels can produce toxic effects and have other impacts.

Some of the cations that are associated with chloride in salts are also plant nutrients. Plants require calcium as a structural component of cell walls and cell membranes and as a messenger within cells. An adequate tissue concentration of calcium is about 5,000 mg/kg.[505] Magnesium is a component of chlorophyll and is involved in protein synthesis and the activation of some enzymes. Adequate tissue concentrations of magnesium range between about 1,500 mg/kg and 3,500 mg/kg.[506] Excesses of calcium and magnesium can result in plants experiencing deficiencies of other nutrients.[507] Potassium regulates the opening and closing of stomates, is important in activating some enzymes, including enzymes related to energy production, and facilitates the synthesis of proteins and starches. Adequate plant tissue concentrations of potassium range between about 3,100 mg/kg and 3,900 mg/kg.[508] Sodium is not required for plant growth, development, or reproduction but is commonly found in plant tissues.

Features of Plant Biology that Can Affect Sensitivity to Chloride Salts

Some features of the biology of plants can make them sensitive to impacts from chloride salts and salinity. Most terrestrial plants are anchored to the substrate by roots or rhizoids. They are unable to escape to another location when conditions become unfavorable. Much of the physiology of terrestrial plants depends on the movement of water from the soil into roots and through shoots into leaves. This is driven by transpiration, which consists of water evaporating from leaves into the atmosphere. This water uptake is also important for the ability of plants to maintain turgor, the rigidity of plant cells and ultimately tissues. Changes in soil conditions, including salinity, can affect the efficiency of the transpiration process. This uptake of water also brings ions from the soil into the plant. While some plants have mechanisms for preventing some ions from entering roots, plants have no means of excreting ions. As a result, ions such as sodium and chloride can build up in plant tissues.

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[501] *N.P. Cain, B. Hale, E. Berkalaar, and D. Morin,* Review of Effects of Road Salt on Terrestrial Vegetation in Canada, *Environment Canada, July 2000.*

[502] *P.J. White and M.R. Broadley, "Chloride in Soils and Its Uptake and Movement Within the Plant,* Annals of Botany*, 88:967-988, 2001.*

[503] Ibid.

[504] *J. Colmenero-Flores, J.D. Franco-Navarro, P. Cubero-Font, P. Peinado-Torrubia, and M.A Rosales, "Chloride as a Beneficial Macronutrient in Higher Plants: New Roles and Regulation,"* International Journal of Molecular Sciences*, 20:4578, doi: 10.3390/ijms20194686, 2019.*

[505] *K. Thor," Calcium—Nutrient and Messenger,"* Frontiers in Plant Science, *10:440, doi: 10.3389/fpls.2019.00440, 2019.*

[506] *W. Guo, H. Nazim, Z. Liang, and D. Yang, "Magnesium Deficiency in Plants: An Urgent Problem,"* The Crop Journal*, 4:83-91, 2016.*

[507] *Evans and Frick 2001,* op. cit.

[508] *A. Rodriguez-Navarro, "Potassium Transport in Fungi and Plants,"* Biochimica et Biophysica Acta*, 1469:1-30, 2000.*

The growth stage a plant is in can affect its sensitivity to chloride salts. For example, seedlings of grasses and herbaceous plants tend to be more sensitive to impacts from road salt than adult plants.[509] Similarly, young trees may be more susceptible to damage from salts than older ones.[510]

Cell division and growth in plants occurs at specific locations called meristems. The meristems responsible for longitudinal growth are typically found at the tips of shoots and roots, although grasses also have them at the base of leaves. Meristems are also found within buds. Salt on foliage tends to be more rapidly transported into these young, rapidly growing tissues.[511] These meristem tissues can be highly sensitive to impacts from salts.

Trees growing in urban environments may be particularly vulnerable to impacts from salts because they are already under stress from other elements of the urban environment.[512] Urban trees often have a small volume of substrate in which to grow. The presence of building foundations, streets, sidewalks, and other underground infrastructure restricts the space available for root growth which reduces the amount of water and nutrients available to the tree. In addition, soil in urban areas is often compacted during development. Compacted soils are more difficult for roots to penetrate and hold less water and oxygen than uncompacted soils. Finally, urban areas often have dense layers of turf grass. This can result in competition between grasses and trees for water and nutrients, reducing the amount available to the trees.

Environmental Factors that Affect Impacts of Chloride Salts on Vegetation

Several environmental factors also affect the impacts that chloride salts and salinity have on vegetation.[513] Many of these factors work through their influence on water relations in plants. Higher temperatures can lead to greater transpiration which can result in greater uptake and absorption of ions, including chloride salts. Higher temperatures can also increase dehydration of plants. Greater exposure to direct sunlight can also lead to more transpiration and increase dehydration. Low humidity and higher wind speeds can also increase transpiration and lead to dehydration. The salinity of the soil serving as a plant's substrate also has an effect. As the salinity of soil water rises, its availability to the plant decreases. Finally, the amount and timing of precipitation and the texture and drainage of the soil affect the availability of water to the plant.

How Plants Are Exposed to Chloride Salts

Plants can be exposed to chloride salts in two different ways. Salts can be deposited on the above ground portions of the plant through physical mechanisms such as aerial deposition caused by splashing and spraying of salt from impervious surfaces, contact with runoff containing salt, or placement of snow containing salt upon the plants. These forms of deposition were discussed in Chapter 2 of this report. This type of direct contact can result in some types of plants experiencing different levels of exposure to chloride. Herbaceous plants, for example, are not usually exposed to salt spray, aerial deposition, or direct contact during the winter as their above ground parts are dead and may be absent during this season.[514] Plants can also be exposed to chloride salts through uptake of ions from the soil and soil water. Introduction of chloride salts to soil and movement of chloride salts through soils is also discussed in Chapter 2 of this Report.

Exposure to chloride salts has been reported to cause several types of injuries to terrestrial plants. Individual plant species can differ in the injuries that they experience depending on the route of exposure and details of plant biology. In particular, different types of injuries have been observed in herbaceous plants versus woody plants, and deciduous woody plants versus evergreen woody plants.

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509 *A.S.N. Liem, A. Hedricks, H. Kraal, and M. Loenen, "Effects of De-Icing Salts on Roadside Grasses and Herbs,"* Plant and Soil, *84:299-310, 1985.*

510 *R.E. Hanes C.W. Zelazney, and R.E. Blaser,* Effects of Deicing Salts on Water Quality and Biota—Literature Review and Recommended Research, *Highway Research Board Report No. 91, 1970.*

511 Ibid.

512 *M. Sieghardt, E. Mursch-Radlgruber, E. Paoletti, E.A.M. Couenberg, A. Dimitrakopoulus, F. Rego, A. Hatzisthathis, and T.B. Randrup, "The Abiotic Urban Environment: Impact of Urban Growing Conditions on Urban Vegetation," Pages 281-23 in: C.C. Konijnendijk, K. Nilsson, T.B. Randrup, and J. Schipperijn (Editors),* Urban Forests and Trees: A Reference Book, *Springer Verlag, Berlin, 2005.*

513 *Levelton Consultants, Ltd.,* Guidelines for the Selection of Snow and Ice Control Materials to Mitigate Environmental Impacts, *National Cooperative Highway Research Program Report No. 577, Transportation Research Board, 2007.*

514 *Cain et al. 2000,* op. cit.

Plant Injuries Caused by Elevated Sodium Chloride Concentration in Soil

Several general symptoms have been reported following exposure of plants to elevated concentrations of sodium chloride in soil.[515] These include reductions in plant growth, damages to leaves, wilting of plants in hot, dry weather, tissue death, reduced or delayed germination of seeds, and nutrient deficiencies. Examples of these impacts are discussed in the next three paragraphs.

Growth in soil with elevated concentrations of sodium chloride can lead to reduced growth and stunting of plants. For example, a greenhouse study found that the dry weight of shoots of two grasses, red fescue (*Fescuta rubra*) and perennial ryegrass (*Lolium perenne*) and two herbs, narrow-leaf plantain (*Plantago lanceolata*) and white clover (*Trifolium repens*), decreased with higher concentration of sodium chloride in soil.[516] Another study reported that the dry weight of leaves and stems and the water content of leaves in common reed (*Phragmites australis*) lessened with increasing soil sodium chloride concentration.[517] This study also found that more sodium accumulated in reed stem tissues at higher soil sodium chloride concentrations. Elevated levels of sodium chloride in soil also led to a decrease in root proliferation and length of shoots in turf grasses.[518] Calcium chloride was reported to cause similar effects on turf grasses.[519]

Plants grown in soil treated with sodium chloride showed damage to leaves.[520] Foliar symptoms included wilting leaves, chlorosis or yellowing, and necrosis or tissue death. Examples of these are shown in Figure 3.11. In deciduous trees and herbaceous plants, this typically began along the margins of the leaves, and progressed to the leaf interior. An example of this is shown in Figure 3.12. In evergreens, foliar symptoms began at the tip of the needle and progressed toward the needle base. In trees, these symptoms typically started near the base of the tree and progressed toward the top. Severely damaged leaves and needles may fall off the plants prematurely and the amount of leaf loss can be substantial. One study found that sumacs (*Rhus typhina*) exposed to sodium chloride in roadside soils were essentially defoliated, with most having lost about 90 percent of their leaves.[521] Leaf damage is often associated with the accumulation of sodium ions in leaf tissues. For example, a study that examined browning of needles in roadside pines (*Pinus* spp.) found that trees showing symptoms of foliar damage had tissue concentrations of sodium 75 times higher than those found in unimpacted trees.[522]

Finally, high concentrations of sodium in soils can displace other cations such as calcium, magnesium, and potassium and cause these cations to be lost from the soil. The mechanisms through which this displacement occurs were discussed in Chapter 2 of this report. This cation loss can lead to nutritional deficiencies in plants.[523]

Plant Injuries Caused by Physical Deposition of Chloride Salts

Physical deposition of salts on plants can also cause injury. This deposition may occur through four mechanisms. Chloride in dust or aerosols in the atmosphere may settle on plants. Chloride may also be deposited on plants in rainfall. Snow that contains chloride may be plowed or placed on plants as part of road, parking lot or driveway clearing. Finally, chloride may be deposited by chloride contaminated snow or water splashing onto plants.

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[515] *Environment Canada,* Priority Substances List Assessment Report: Road Salts*, 2001.*

[516] *K.F. Akbar, A.D. Headley, W.H.G. Hale, and M. Athar, "A Comparative Study of De-Icing Salts (Sodium Chloride and Calcium Magnesium Acetate) on the Growth of Some Roadside Plants of England,"* Journal of Applied Sciences and Environmental Management*, 10:67-81, 2006.*

[517] *M. Gorai, M. Ennejeh, H. Dhemira, and M. Neff, " Influence of NaCl-Salinity on Growth, Photosynthesis, Water Relations and Solute Accumulation in* Phragmites australis," Acta Physiologiae Plantarum*, 33:963-971, 2011.*

[518] *J.L. Eggens, "De-icing Salt Injury to Turfgrasses,"* Landscape Ontario*, 8:17-19, 1980.*

[519] *W.E. Cordukes and A.J. MacLean, "Tolerance of Some Turfgrass Species to Different Concentrations of Salt in Soils,"* Canadian Journal of Plant Science*, 53:69-73, 1973.*

[520] *See, for example, M.A. Dirr, "Tolerance of Seven Woody Ornamentals to Soil-Applied Sodium Chloride,"* Journal of Arboriculture*, 4:162-165, 1978.*

[521] *G.E. Bryson and A.V. Barker, "Sodium Accumulation in Soils and Plants along Massachusetts Roadsides,"* Communications in Soil Science and Plant Analysis*, 33:67-78, 2002.*

[522] Ibid.

[523] *F.W. Holmes, "Salt Injuries to Trees,"* Phytopathology*, 51:712-718, 1961.*

Figure 3.11
Examples of Plant Damage from Chloride Salts in Soil

Chlorosis on Raspberry Leaf

Elm Leaves Showing Necrosis

Source: Wikimedia Commons

Such transport typically occurs through young shoots, buds, needles, and leaves. These tissues may show evidence of injuries from the salt. By contrast, direct injuries to mature bark by chloride salts has not been reported.[524] Most of the literature examining physical deposition of salt addresses aerial deposition.

Several general symptoms have been reported following physical deposition of chloride salts on plants. These include diebacks of buds and twigs, delays in bud opening, failure to flower, reduced fruit yields, reduced stem and leaf growth, and damage to leaves. On large plants like trees, these impacts are often heavier on the sides of the plant facing the salt source and/or to the height reached by salt spray.[525] An example of this is shown in Figure 3.13. In this example snow plowed from a driveway was piled next to and upon the bottom branches of the trees. The impacts of physical deposition of chloride salts on plants are further discussed in the next seven paragraphs.

Physical deposition of salt on plants can lead to dieback of buds and twigs.[526] This can lead to mishappen plants. For example, death of stems and buds on first year shoots may result in multiple new shoots sprouting below the dead branch tip. This can result in the plant developing a brush-like morphology. In addition, bud and twig dieback can lead to thinning of tree crowns and death of large branches causing damage to tree crowns.[527] A study examining the impact of spraying roads with magnesium chloride for dust suppression found that about 60 percent of lodgepole pines (*Pinus contorta*) near the roads had damage to their crowns.[528] The amount of damage to individual pine trees correlated with the concentration of chloride in their needles. The amount of crown damage was not related to the concentrations of chloride or magnesium in the soil.

[524] *Cain et al. 2000,* op. cit.

[525] *E-.L. Viskari and L. Kärenlampi, "Roadside Scots Pine as an Indicator of Deicing Salt Use—A Comparative Study from Two Consecutive Winters,"* Water, Air, and Soil Pollution*, 122:405-419, 2000.*

[526] Ibid.

[527] *L. Bäckman, and L. Folkerson,* The Influence of Deicing Salt on Vegetation, Groundwater, and Soil along Highways E20 and 48 in Skaraborg County During 1994*, Swedish National Road and Transport Research Institute Report No. 775A, 1995.*

[528] *B.A. Goodrich, R.D. Koski, and W.R. Jacobi, "Conditions of Soils and Vegetation along Roads Treated with Magnesium Chloride for Dust Suppression,"* Water, Air, and Soil Pollution*, 198:165-188, 2009.*

Flower buds are especially sensitive to the effects of salt spray.[529] Common observations supporting this is that the sides of trees exposed to road salt spray may have no flowers, and the shrubs adjacent to highways may have flowers only below the snowline. A progression of injuries related to flowering with exposure to increasing levels of deicing salt has been reported for apple trees near highways.[530] At lower levels of salt deposited on twigs, the apple trees showed a slight reduction in flowering. Greater exposure led to a marked reduction in flowering. At even higher levels of exposure to chloride salt spray, flowering shoots, that are spurs off vegetative shoots began to die. Still higher exposure led to a marked dieback of flowering shoots on the apple trees.

The impacts of physical deposition of chloride salts on flowering can lead to reduced fruit yields. One study examined the impacts of aerial deposition of road salt on lowbush blueberries (*Vaccinium angustifolium*) in two commercial fields adjacent to a major highway in Nova Scotia.[531] Examination of plants showed that the concentrations of road salt on exposed plant stems were highest on plants that were next to the highway and decreased with longer distances from the road. The number of blossoms on and fruit yields from the blueberry plants were lowest near the road and rose with increasing distance from the road. The number of live flower buds and blossoms per plant and the yield of fruit per plant was inversely proportional to the concentration of road salt found on the stems. Placing plastic shields over blueberry plants near the road protected them from salt deposition from spray. Plants protected in this manner had lower concentrations of salt on their stems than unprotected plants located the same distance from the road. The shields increased the number of live buds and blossoms on the plants and the yields of fruit. Aerial deposition of road salt has also been shown to lower fruit yields from peach trees.[532]

Figure: 3.12
Bird Nest Fern (*Asplenium nidus*) Showing Salt Damage

Source: Wikimedia User Toyoba2

Figure: 3.13
Arbor Vitae Trees Damaged by Salt in Snow Piles

Source: Laura Herrick, SEWRPC

Physical deposition of chloride salts can lead to reduced growth in plants. New growth in plants impacted by salts is often less than that in unimpacted plants.[533] For example, spruces at locations impacted by road salt were shorter and had smaller diameters at breast height than those at unimpacted sites.[534] This may be related

[529] *G. Hofstra, R. Hall, and G.P. Lumis, "Studies of Salt-Induced Damage to Roadside Plants in Ontario,"* Journal of Arboriculture, *5:25-31, 1979.*

[530] *G. Hofstra and G.P. Lumis, "Levels of Deicing Salt Producing Injury on Apple Trees,"* Canadian Journal of Plant Science, *55:113-115, 1975.*

[531] *L.J. Eaton, J. Hoyle, and A. King, "Effects of Deicing Salt on Lowbush Blueberry Flowering and Yield,"* Canadian Journal of Plant Science, *79:125-128, 1999.*

[532] *J. Northover, "NaCl Injury to Dormant Roadside Peach Trees and its Effect on the Incidence of Infections by* Leucostoma *spp.,"* Phytopathology, *77:835-840, 1987.*

[533] *Hofstra et al. 1979,* op. cit.

[534] *M. Kayama, A.M. Quoreshi, S. Kitaoka, Y.K. Tahashi, Y. Sakamoto, Y. Maruyama, M. Kitao, and T. Korke, "Effects of Deicing Salts on the Vitality and Health of Two Spruce Species,* Picea abies *Karst., and* Picea glehnii *Masters Planted Along Roadsides in Northern Japan,"* Environmental Pollution, *124:127-137, 2003.*

to the growth of impacted plants resuming later in the growing season than uninjured plants. One study found that salt deposition on deciduous trees can delay resumption of spring growth by as much as three weeks.[535] Aerial deposition of chloride salts can also damage leaves. For example, a greenhouse study examined the effects of spraying water containing different concentrations of sodium chloride on two grasses, red fuscue (*Fescuta rubra*) and perennial ryegrass (*Lolium perenne*) and two herbs, narrow-leaf plantain (*Plantago lanceolata*) and white clover (*Trifolium repens*).[536] The study found that the amount of damage to leaves rose with increasing sodium chloride concentration in the spray. It also found that the grasses tested were more tolerant of sodium chloride in the spray than the herbs.

Aerial deposition of chloride salts can also damage needles on evergreen trees. This damage tends to have distinct symptoms. Initially, the tips of mature needles exposed to salt turn yellow or brown. This discoloration moves toward the base of the needle, ultimately resulting in complete yellowing. The damaged needles then fall off the tree. An example of salt damage to pine needles is shown in Figure 3.14.

Figure: 3.14
Pine Needles Showing Salt Damage

Source: Flickr User Mary Lou Fairweather

Damage from salt shortens the lives of conifer needles. For example, one study in Japan found that Norway spruce (*Picea abies*) and Sakhalin spruce *(Picea glehnii*) impacted by road salt lost their needles more quickly than unimpacted spruces.[537] The amount of needle shedding increased as the concentrations of chloride and sodium in the needles increased. As a result, the crowns of trees examined at locations impacted by aerial deposition of road salt had lower densities of needles than those at unimpacted sites. Examination of needles using scanning electron microscopy showed that the stomates of needles from salt-impacted sites were covered with large amounts of dust, which likely interfered with gas exchange and transpiration. This dust was absent from stomates of needles from unimpacted sites. These injuries affected the photosynthetic capabilities of the needles. Two-year-old needles from spruces growing at locations impacted by aerial deposition of road salt showed light-saturated ratues of photosynthesis that were less than half of those observed in needles from unimpacted sites.[538]

Effects of Injuries on Plant Vigor

Repeated injury from chloride salts can reduce the vigor of perennial plants and make the plants more sensitive to other hazards such as disease, insects, drought, or winter injury.[539] An examination of Scots pine (*Pinus sylvestris*) found that needles on trees growing near a heavily salted highway were common infected with pine needle cast fungus and aphid eggs. These plant pests were not observed on needle growth on trees at a lightly salted site.

Spatial and Temporal Patterns of Injury to Terrestrial Plants from Road Deicing

Certain patterns of plant injury have been associated with using chloride salts for road deicing.[540] Spatially, injury occurs in a linear pattern along roads or in areas where road runoff collects. Injury tends to be

[535] *E. Sucoff,* Effect of Deicing Salts on Woody Vegetation Along Minnesota Roads, *Minnesota Agricultural Experiment Station Technical Bulletin No. 303, 1975.*

[536] *K.F. Akbar et al. 2006,* op. cit.

[537] *M. Kayama, et al. 2003,* op. cit.

[538] Ibid.

[539] *Sucoff 1975,* op. cit.

[540] *G.P. Lumis, G. Hofstra, R. Hall, "Sensitivity of Roadside Trees and Shrubs to Aerial Drift of Deicing Salt,"* Canadian Journal of Plant Science, *8:475-477, 1973; M.A. Dirr, "Selection of Trees for Tolerance to Salt Injury,"* Journal of Arboriculture, *2:209-216, 1976.*

more severe on the side of the plant facing the road and injury decreases with distance from the road. For instance, one study examining damage from road salt to roadside trees and shrubs found that the levels of visible injury to woody plants fell to background levels between 130 and 330 feet from the edge of the pavement.[541] Injury is often worse downwind of the road. Parts of woody plants that are covered by snow or sheltered from spray lack injury symptoms. Portions of trees that extend above the salt spray zone are not injured or are less injured than those in the salt spray zone. Also, salt spray injury extends only a short distance into plants with dense foliage.

Temporal patterns of injury to plants have also been reported.[542] Injury to evergreen trees and shrubs becomes evident in late winter and extends into the growing season. The appearance of injury can be quite sudden, occurring with the onset of temperatures that are above freezing.[543] For evergreens and shrubs this is when transpiration begins and may be related to the obstruction of stomates which was discussed previously in the section on plant injuries due to aerial deposition of chloride salts. Injury to deciduous trees and shrubs become evident in spring when growth resumes and extends into the growing season.

<u>Mechanisms Underlying Chloride Salt Impacts on Terrestrial Plants</u>

Several mechanisms likely underlie the effects of chlorides and chloride salts on terrestrial plants. First, accumulation of sodium in soil can cause deterioration of soil structure which was discussed in Chapter 2 of this Report. Such deterioration can reduce soil permeability. This reduction makes soil less suitable as a substrate for plant growth by reducing the movement of air and water into and through soil. As also discussed in Chapter 2, accumulation of sodium affects cation exchange processes in soil, which can lead to nutrient imbalances in plants. These effects can negatively impact seedling emergence and root growth.

Chloride salts damage plants through osmotic effects. Salt deposited on the leaves causes water to move out of plant cells.[544] Enough water loss leads to the membrane in a plant cell being pulled away from its cell wall, which can cause collapse of plant tissue.[545] Osmotic effects from chloride salts in soil can reduce the ability of plants to take up water and nutrients. For example, one study found that chloride salts in the soil reduced the uptake of nitrate and its accumulation in crop plants.[546] Reductions in water and nutrient uptake from chloride salts can lead to reduced plant growth, nutrient deficiencies, and the appearance of drought-like symptoms. In essence, salt can act as a non-selective herbicide by creating osmotic stresses that lead to water loss from affected plant tissues.

Chloride salts in soils can also injure plants by disrupting the microscopic organisms in the rhizosphere. This is a narrow region of soil surrounding roots that is affected by secretions from the roots (see Figure 3.15). This zone contains bacteria, fungi, and small animals like nematode worms that are associated with the plant. Interactions between the plant and these organisms are important in maintaining plant health.[547] Maintenance of rhizosphere biota is important in maintaining the plant abilities to take up water and nutrients. Fungi and bacteria in the rhizosphere can protect plants against pathogens through ecological processes such as competition.

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[541] *Bäckman, and Folkerson 1995,* op. cit.

[542] *Lumis et al. 1973,* op. cit.*; Dirr 1976,* op. cit.

[543] *Hofstra et al. 1979,* op. cit.

[544] *E.M. Smith, "Tree Stress from Salts and Herbicides,"* Journal of Arboriculture*, 1:201-205, 1975.*

[545] *W.E. Barrick and H. Davidson, "Deicing Salt Spray Injury in Norway Maple as Influenced by Temperature and Humidity Treatments,"* HortScience*, 15:203-205, 1980.*

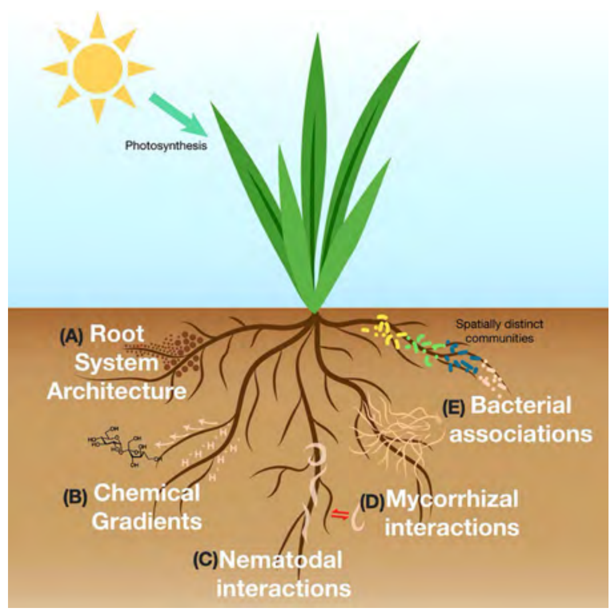
[546] *R. Munns and A. Termaat, "Whole-Plant Responses to Salinity,"* Australian Journal of Plant Physiology*, 13:143-160, 1986.*

[547] *L. Moulin, A. Munive, B. Dreyfus, and C. Boivin Masson, "Nodulation of Legumes by Members of the ß-Subclass of Proteobacteria,"* Nature*, 411:948-950, 2001.*

Accumulation of chloride salts in soil can reduce the diversity of organisms in the rhizosphere. In one study, a solution containing deicing salt was applied to soil surrounding the ornamental shrub Japanese spindle (*Euonymus japonica*) for 27 days.[548] As a result of salt application, the diversity of bacteria species in the top six inches of soil decreased. More importantly, the diversity and evenness of fungal species in the top 18 inches of soil decreased. The decrease in evenness suggests that the fungal community was dominated by a few salt-tolerant species by the end of the experiment.

Chloride salts may cause some plant injuries through interference with assimilation and incorporation of inorganic nitrogen into plant tissue. In one experiment, young barley plants grown in pots were watered with a sodium chloride solution and radioactively labelled inorganic ammonium nitrate.[549] Less nitrogen was incorporated into amino acids and protein in treated plants than in controls. In addition, inorganic nitrogen compounds accumulated in the tissues of treated plants. These chloride salt effects were more pronounced in plant shoots than in roots.

Figure: 3.15
Plant Rhizosphere



Source: Wikimedia Commons User M. O. Yee

Accumulation of sodium chloride in plant cells can interfere with cellular process. This accumulation can inhibit the activity of some enzymes.[550] In addition, accumulation of sodium chloride in plant cells can damage cell membranes. Because of this, plant cells will sometimes compartmentalize sodium chloride by directing it to the central cell vacuole; however, there are limits to the extent that plants are able to do this.

Photosynthesis is another cellular process that sodium chloride may impact. Exposure to sodium chloride can lead to a loss of plant photosynthetic capacity which leads to slower or reduced growth.[551] This happens through at least two different mechanisms. First, higher sodium chloride in soils or plant tissue can cause reductions in the concentration of chlorophyll in leaves.[552] This reduces the ability of the plant to capture light, leading to lower photosynthetic capacity. Second, higher soil salinity can lead to a decrease in carbon dioxide assimilation which was observed in the common reed *Phragmites australis*.[553] Lower carbon dioxide assimilation may be related to conductance of gases and water vapor through stomates on leaves. This suggests that when confronted with higher concentrations of sodium chloride in soil or on leaves, plants may close their stomates to reduce water loss. The opening and closing of stomates is illustrated in Figure 3.16.

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[548] *C. Ke, Z. Li, Y. Liang, W. Tao, and M. Du, "Impacts of Chloride De-Icing Salt on Bulk Soils, Fungi, and Bacterial Populations Surrounding the Plant Rhizosphere,"* Applied Soil Ecology, *72:69-78, 2013.*

[549] *H.M. Helal and K. Mengel, "Nitrogen Metabolism of Young Barley Plants as Affected by NaCl—Salinity and Potassium,"* Plant and Soil, *51:457-462, 1979.*

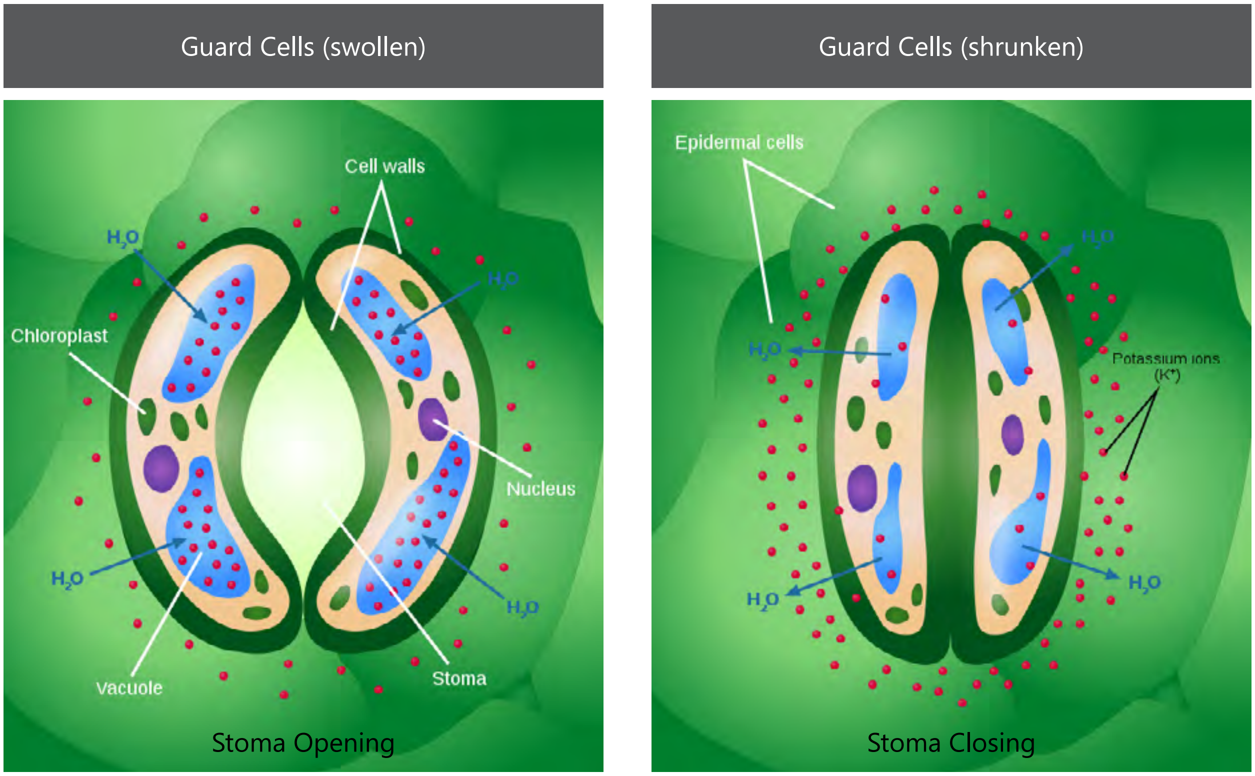
[550] *K.M. Volkmar, Y. Hu, and H. Steppuhn, "Physiological Responses of Plants to Salinity: A Review,"* Canadian Journal of Plant Science, *78:1-27, 1998; R. Munns, "Comparative Physiology of Salt and Water Stress,"* Plant, Cell & Environment, *25:239-250, 2002.*

[551] *Cain et al. 2000,* op. cit.

[552] *J.P. Syversten, J. Lloyd, and P.E. Kriedmann, "Salinity and Drought Stress Effects on Foliar Ion Concentrations, Water Relations, and Photosynthetic Characteristics of Orchard Citrus,"* Australian Journal of Agricultural Research, *39:619-627, 1988.*

[553] *M. Gorai, M. Ennajeh, H. Khemira, and M. Neffati, "Combined Effect of NaCl-Salinity and Hypoxia on Growth, Photosynthesis, Water Relations, and Solute Accumulation in* Phragmites australis *Plants,"* Flora, *205:462-470, 2010.*

Figure: 3.16
Stomates Opening and Closing on Plant Leaves



Water availability in leaves open and close stomates. When water availability is high, water flows into adjacent cells, opening the stoma pore. When water is less availble, water flows out of the adjacent cells, closing the pore.

Source: Wikimedia User Ali Zifan

Three findings from additional research provide support for this stomate closure hypothesis.[554] First, the rate at which photosynthesis occurs in common reed is correlated with the rate of gas conductance through stomates. Second, the rate of transpiration decreases with increasing concentration of sodium chloride in soil. Third, the rate of photosynthesis decreases with increasing soil sodium chloride concentration.

Plant Ability to Compensate for or Tolerate Chloride Salts

Plant species differ in their sensitivity to injury from chloride salts. This is partially related to plant growth forms and life histories. Herbaceous and annually seeded plants may not be exposed to salt spray or dust during winter and spring, thus avoiding some injury to stems and leaves. Similarly, during winter, above ground growth from previous growing seasons for many perennial, biennial, and overwintering annual plants die back. The overwintering parts of these plants are underground and protected from exposure to salt from dust and spray.[555] By contrast, the above ground parts of woody trees, shrubs, and vines persist through the winter and are subject to direct contact from salts. Nevertheless, all these plants may be exposed to chloride salts in soils.

Some patterns have been observed in plant sensitivity to chloride salts. Shrubs and grasses are generally more tolerant to sodium chloride than trees.[556] Conifers are generally more sensitive to injury than deciduous

[554] *M. Gorai et al. 2011,* op. cit.

[555] *Cain et al. 2000,* op. cit.

[556] *Sucoff 1975.* op. cit.

trees.[557] Differences in sensitivity among conifer species are related to the amount of foliar uptake.[558] While injury to needles tends to occur at about the same internal chloride concentration, differences in uptake have been observed that are related to at least two structural differences among the needles of different species. First, needles that are flatter have a higher surface-to-volume ratio and take up salt more rapidly than rounder needles. Second, needles with a thicker cuticle take up salt less readily. Both these qualities vary among conifer species.

Botanists and horticulturalists have classified plants by relative tolerance to sodium chloride. Appendix C summarizes this classification.

Some plants have mechanisms that allow them to compensate for some impacts from chloride salts. Plants may partially compensate for osmotic stress by increasing the concentrations of solutes in their cytoplasm. For example, cellular concentrations of sugars and the amino acid proline in *Phragmites australis* cells increased with higher exposure to sodium chloride.[559] The presence of these solutes draw water into tissues[560] and this water movement balances osmotic potential and protects enzymes. There are limits, however, to the ability of a plant to do this.

Finally, some plants are able to exclude sodium and/or chloride ions from entering their roots or can immobilize these ions in root and stem tissue.[561] This ability is not perfect and with continued exposure, sodium and chloride ions will accumulate in leaves over time. In addition, woody plants appear to control entry of sodium ions more efficiently than they control entry of chloride ions.

Vertebrates

Terrestrial vertebrates are animals with backbones that live predominantly or entirely on land. They vary in size and weight. For example, the ruby-throated hummingbird (*Archilochus colubris*) is a small bird found in Wisconsin. An adult may be as small as 2.8 inches long and weigh as little as 0.12 ounce. By contrast, adult male black bears (*Ursus americanus*) may be four to six feet long and weigh over 300 pounds. There are three groups of terrestrial vertebrates: reptiles, birds, and mammals.

Terrestrial vertebrates perform several roles in biological communities. They occupy all consumer categories in food webs. This includes detritivores; herbivores that feed on plant material; and predators that feed on invertebrates or other vertebrates. Some are generalists or omnivores that feed on an array of food items. Many also serve as prey to other organisms.

Some terrestrial vertebrates also have an important role in outdoor recreation in Wisconsin. People in the State commonly hunt mammals such as deer, bear, and small mammals and birds such as ducks, geese, and turkey. In addition, people trap furbearers such as mink, fox, and muskrat. Hunting has a large economic impact on Wisconsin. A survey by the U.S. Census Bureau estimated that hunting generated about $2.5 billion in expenditures in Wisconsin in 2011, the most recent year for which data were available.[562] The same survey estimated that wildlife watching, including observing, photographing, and feeding wildlife, generated about $1.5 billion in expenditures.

Limited data are available on the effects of chloride salts on terrestrial vertebrates. With the exception of turtles, which were discussed in the section on the effects of chloride on aquatic organisms, a search of the literature found no studies examining impacts on reptiles. Most of the studies that examine effects on birds address passerine or perching birds, especially seed-eating finches. Many of the studies that examine the effects on mammals address large ungulates such as moose or deer.

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[557] *Hanes et al. 1970,* op. cit.

[558] *Hofstra et al. 1979,* op. cit.

[559] *Gorai et al. 2010,* op. cit.

[560] *M. Ashaf and M.R Foolad, "Role of Glycine Betaine, and Proline in Improving Plant Abiotic Stress Resistance,"* Environmental and Experimental Botany*, 59:206-216, 2007.*

[561] *Munns and Tester 2008,* op. cit.

[562] *U.S. Census Bureau,* 2011 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation: Wisconsin*, FHW/11-WI (RV), Revised October 2018.*

Features of Vertebrate Biology that Can Affect Sensitivity to Chloride Salts

Some features of vertebrate biology may affect the sensitivity of these animals to impacts from chloride salts. All vertebrates require sodium as an essential nutrient, generally in amounts of milligrams per gram of food consumed. Depending on their diet, obtaining sufficient sodium to meet nutritional requirements may be difficult for some species. Plant material often contains insufficient sodium to meet the needs of herbivores, and animals that feed mostly on plant material may need to find supplemental sources. For example, herbivorous and granivorous birds will seek out salt due to the sodium-deficient nature of their diet.[563] Similarly, mammalian herbivores, including ungulates like deer, will seek out sources of salt such as mineral licks to obtain sodium.[564] The need for sodium in some species can be driven by seasonal processes. For example, seasonal loss of sodium from the body due to antler development and gestation may compel deer to seek out sodium.[565] Because of these needs, the presence of road salt may be one of the factors inducing white-tailed deer, for example, to forage along roads.[566]

Birds may also ingest salt for use as grit. Birds use grit to improve the mechanical grinding of food in their gizzards.[567] The amount of grit that they ingest depends on how long grit is retained in their gizzards. When birds have free access to grit, they may consume and excrete a considerable amount daily.[568] House sparrows (*Passer domesticus*), for example, tend to choose grit particles with characteristics similar to those of road salt.[569] They prefer angular and oblong particles over rounded and spherical ones,[570] yellow or white colored grit over black and blue grit,[571] and grit in the size range of 0.1 to 2.4 millimeters (mm).[572] It should be noted that the sizes of road salt particles often overlap the sparrow's preferred size range for grit. The size range of road salt particles coming from a mine in Ontario were reported as ranging between 0.6 and 9.5 mm. Once it is applied to a road, salt undergoes gradual size reduction as it enters solution. Thus, at some time after application, salt particles will be at the preferred grit sizes for many bird species.[573] This suggests that many bird species, in addition to house sparrows, may use road salt particles as grit. For some species, this could be a major route of exposure to chloride.

Toxicity Effects of Chloride Salts to Vertebrates

Consumption of chloride salts can produce toxic effects in birds and mammals. Birds and small mammals are generally more susceptible to toxic effects from sodium chloride.[574] By contrast, the chloride tolerance of large mammals is usually quite high, as long as adequate drinking water is available. Water availability is an important factor in toxicity of sodium chloride to vertebrates. In general, the effects of salt consumption increase when water is in short supply, such as during winter.[575]

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[563] *J. Schulkin,* Sodium Hunger: The Search for a Salty Taste, *Cambridge University Press, Cambridge, Massachusetts, 1991.*

[564] *H.P. Weeks, Jr., and C.M. Kirkpatrick, "Adaptations of White-Tailed Deer to Naturally Occurring Sodium Deficiencies,"* Journal of Wildlife Management*, 40:610-625, 1976.*

[565] Ibid.

[566] *G. Fieldhammer, J. Gates, D. Harman, A. Loranger, and K. Dixon, "Effects of Interstate Highway Fencing on White-Tailed Deer Activity,"* Journal of Wildlife Management*, 50:497-503, 1986.*

[567] *J.P. Gionfriddo, and L.B. Best, "Grit Use by House Sparrows: Effects of Diet and Grit Size,"* The Condor*, 97:57-67, 1995.*

[568] *J.C. Alonso, "Grit in the Gizzard of Spanish Sparrows (*Passer Hispaniolensis*),"* Vogelwarte*, 33:135-143, 1985.*

[569] *T.K. Bollinger, P. Mineau, and M.L. Wickstrom, "Toxicity of Sodium Chloride to House Sparrows (*Passer domesticus*),"* Journal of Wildlife Diseases*, 41:363-370, 2005.*

[570] *L.B. Best and J.P. Gionfriddo, "Effects of Surface Texture and Shape on Grit Selection by House Sparrows and Northern Bobwhite,"* Wilson Bulletin*, 106:589-695, 1994.*

[571] *J.P. Gionfriddo, and L.B. Best, "Grit Color Selection by House Sparrows and Northern Bobwhites,"* Journal of Wildlife Management*, 60:836-842, 1996.*

[572] *Gionfriddo and Best 1995,* op. cit.

[573] *Environment Canada 2001,* op. cit.

[574] *P.H. Jones, B.A. Jeffrey, P.K. Watler, and H. Hutchon, "Environmental Impact of Road Salting," Chapter 1 pages 1-116 in F.M. D'Itri (editor),* Chemical Deicers and the Environment, *Lewis Publishers, Boca Raton, Florida, 1992.*

[575] *P. Mineau and L.J. Brownlee, "Road Salts and Birds: An Assessment of the Risk with Particular Emphasis on Winter Finch Mortality,"* Wildlife Society Bulletin*, 33:835-841, 2005.*

A literature review found 12 published reports of bird kills associated with road salts.[576] At least two of the reports involved over 1,000 birds. These bird kills involved several species such as red crossbill (*Loxia curvirostra*), white-winged crossbill (*Loxia leucoptera*), pine siskin (*Spinus pinus*), evening grosbeak (*Hesperiphona vespertina*), bobwhite quail (*Colinus virginianus*), ring-necked pheasant (*Phasianus colchicus*), and domestic pigeon (*Columba livia domsitica*). The authors of the review argue that the number of reports likely underestimate the occurrence of bird kills due to road salt because of difficulties in finding avian carcasses, scavenging by other animals at kill sites, and the generally low rates of reporting of wildlife mortality incidents. They also argue that the number of anecdotal reports of bird kills they were able to find implies that such events are more common than the literature would suggest.

Among songbirds, highway mortality events are most commonly reported for some groups of seed-eating finches.[577] The cause of this mortality is unclear. These birds may be attracted to salted roadways due to a need for dietary sodium.[578] Alternatively, they may be ingesting salt for use as grit.[579]

The effects of sodium chloride on the house sparrow (*Passer domesticus*) have been studied in detail.[580] Although they have considerable dietary flexibility, house sparrows typically feed on seeds of grains and weeds.[581] Seeds generally make up about 90 percent of their diet. The LD50 for house sparrows for sodium chloride is 3,108 mg per kg body weight.[582,583] Given that the average weight of a house sparrow is slightly less than one ounce, this is equivalent to a dose of about 90 mg, or about five 2.4-millimeter-long salt granules. This represents a tiny fraction of the number of grit particles typically found in house sparrow gizzards.[584]

Exposure to sodium chloride also causes sublethal effects in house sparrows.[585] Edema or swelling of the gizzard occurs about one hour after birds receive a dose of 500 mg per kg body weight or about 14 mg for the average size sparrow. Clinical signs of effects appeared at doses of 1,500 mg per kg body weight or about 42 mg for the average size sparrow. These included reduced activity, reduced response to visual and auditory stimuli, loss of coordination and balance, and inability to fly or perch. In instances where sodium chloride doses did not result in the birds dying, it took them five to eight hours to recover from the effects.

Aberrant behavior in birds exposed to road salt has been reported in several studies.[586] Reported behavior include the birds appearing fearless and being more easily approached. These reports also indicated that the birds appeared weak, and exhibited slow movement, tremors, and partial paralysis. These symptoms are similar to those seen in laboratory studies examining the toxicity of road salt to birds.

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576 Ibid.

577 *R. Tozer, "Red Crossbills Feeding at Mineral Sources,"* Ontario Birds*, 12:102-108, 1994.*

578 *D. Frasier, "Mammals, Birds and Butterflies at Sodium Sources in Northern Ontario Forests,"* Canadian Field Naturalist*, 99:365-367, 1985.*

579 *T.K. Bollinger, P. Mineau, and M.L. Wickstrom, "Toxicity of Sodium Chloride to House Sparrows (*Passer domesticus*),"* Journal of Wildlife Diseases*, 41:363-370, 2005.*

580 Ibid.

581 *T.R. Anderson,* Biology of the Ubiquitous House Sparrow: From Genes to Populations*, Oxford University Press, Oxford, United Kingdom, 2006.*

582 *Bollinger et al. 2005,* op. cit.

583 *For organisms ingesting a toxin, acute toxicity is often expressed as the LD50. This is the dose of the toxin at which 50 percent of the organisms die over the duration of the test. A higher LD50 indicates lower toxicity to the organism, while a lower LD 50 indicates greater sensitivity to the toxin.*

584 *Gionfriddo and Best 1995,* op. cit.

585 *Bollinger et al. 2005,* op. cit.

586 *These are reviewed in: D.L. Kelting and C.L. Laxson,* Review of Effects and Costs of Road De-Icing with Recommendations for Winter Road Management in the Adirondack Park*, Adirondack Watershed Institute Report No. AWI 2010-01, 2010.*

Toxicity of road salt has been less studied in small mammals than in birds. One report of a bird kill also reported a kill of cottontail rabbits (*Sylvilagus floridanus*) associated with toxicity from road salt.[587]

Role of Road Salt in Wildlife-Vehicle Collisions

The presence of salt along roads and in ponds and pools near roads may contribute to wildlife-vehicle collisions. Birds, for example, are commonly struck by vehicles as they consume salt off of roadways.[588] These collisions are often attributed to the attraction of the salt, either as a dietary supplement or for grit, and the inability of birds to recognize the threat posed by an approaching motor vehicle.[589] It has also been suggested that the disorientation caused by salt consumption may lead birds to have increased susceptibility to collisions with vehicles.[590]

The presence of salt on and adjacent to roads may also be a factor in collisions involving mammals. While this appears to not have been formally studied, small mammals such as woodchucks (*Marmota monax*), porcupines (*Erethizon dorsatum*), and showshoe hares (*Lepus americanus*) have been reported as being frequently observed feeding on roadside salt.[591]

Much of the research on the effect of road salt on wildlife-vehicle collisions has focused on large ungulates, especially moose (*Alces alces*). This reflects the threat to public safety posed by collisions between vehicles and deer and moose. For example, an annual average of about 2,900 deer-vehicle collisions occurred in southeastern Wisconsin in the years 2017 through 2020.[592]

Several observations support the idea that road salt may contribute to attracting these large mammals to roads and increase the likelihood of collisions with vehicles. Radio-collared moose in New Hampshire were found to extend their ranges to include roadside pools contaminated with road salt.[593] A study in Ontario found that peak incidence of moose-vehicle collisions occurred during periods when moose had the highest sodium needs and not during periods of the highest vehicular traffic.[594] Sightings of moose were also highest and about half of all collisions occurred at or near roadside pools containing salt. The roadside pools used by moose tended to have high concentrations of sodium and chloride. This last observation was similar to results from a study in Quebec that found that moose visits to roadside pools were greatest at pools with high concentrations of sodium and chloride.[595] Removal of salt deposits and pools from roadsides at a site in Quebec reduced the number of moose-vehicle collisions and the number of moose road crossings during spring and summer.[596] Finally, it has been observed that deer and moose drinking

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[587] *D.O. Trainer and L. Karstad, "Salt Poisoning in Wisconsin Wildlife,"* Journal of the American Veterinary Medicine Association*, 13:614-617, 1960.*

[588] *Mineau and Brownlee 2005,* op. cit.

[589] *K.D. Baker, "An Observation of Bird Mortality on Highways,"* The Blue Jay, *25:79-80, 1965; D. Leatherman, "Crossbill Attraction to Salt: A Colorado Episode,"* Colorado Field Ornithologist Journal*, 23:102, 1989.*

[590] *T. Topfer, "Suspected Road Salt Poisoning in Bohemian Waxwings* Bobycilla garrulous *(Aves: Passeriformes: Bombycillidae),"* Vertebrate Zoology*, 60:174-174, 2010.*

[591] *A.H. Hubbs and R. Boostra,* Study Design to Assess the Effects of Highway Median Barriers on Wildlife*, Ontario Ministry of Transportation, MAT-94-03, 1995.*

[592] *Wisconsin Department of Natural Resources,* Deer Vehicle Collisions*, dnr.wi.gov/wideermetrics/DeerStts.aspx?R=collisions, accessed January 23, 2023.*

[593] *B.K. Miller and J.A. Litvaitis, "Use of Roadside Salt Licks by Moose,* Alces alces, *in Northern New Hampshire,"* Canadian Field Naturalist*, 106:112-117, 1992.*

[594] *D. Frasier and E.R. Thomas, "Moose-Vehicle Accidents in Ontario: Relation to Highway Salt,"* Wildlife Society Bulletin*, 10:261-265, 1982.*

[595] *Kelting and Laxson 2010,* op. cit.

[596] *P.D. Grosman, J.A.G. Jaeger, P.M. Biron, C. Dussault, and J.-P. Ouellet, "Reducing Moose-Vehicle Collisions through Salt Pool Removal and Displacement: An Agent-Based Modeling Approach,"* Ecology and Society*, 14:17, www.ecologyandsociety.org/vol14/iss2/art17, 2009.*

salty water tend to lose their fear of humans and vehicles.[597] The makes them prone to bolt, sometimes into the path of a vehicle instead of moving away as they normally would.

Summary of Effects on Organisms

Increased levels of chloride salts in the environment can result in a variety of impacts on organisms. These effects can vary depending on the type of organism. Chloride impacts can also vary depending on how the organism is exposed.

Many of the impacts of chloride salts on organisms result from the toxicity of chloride or the cations associated with chloride to organisms. The threshold at which toxic effects occur varies among groups of organisms, as well as within groups. One way to compare the sensitivity of different organisms to the most severe effects from chloride is to determine their LC50s, the exposure concentration at which half the test organisms die over the course of the test. As measured by 96-hour LC50s, groups of organisms vary widely in their sensitivity to chloride salts. For instance, zooplankton are relatively sensitive to chloride toxicity with 96-hour LC50s ranging between about 1,000 mg/l and 1,600 mg/l. Freshwater fish are much less sensitive with 96-hour LC50s for adults ranging between 3,000 mg/l and 13,000 mg/l. Different taxa within larger groups also vary in their sensitivity to chloride. While 96-hour LC50s for aquatic insects range between about 400 mg/l and 8,100 mg/l, some insect groups show more sensitivity than others. Mayflies are quite sensitive to chloride with 96-hour LC50s ranging between 425 mg/l and 2,800 mg/l. Caddisflies are less sensitive with 96-hour LC50s ranging between 2,100 mg/l and 8,100 mg/l.

Many other factors can affect the toxicity of chloride salts to organisms. These include factors related to level of exposure the organism experiences such as the dose or concentration of chloride and length of time that the organism is exposed. Environmental factors such as temperature, water hardness, the presence of other chemicals, and the presence of food can affect the toxicity of chloride. Similarly, elements of the biology of a species, such as the developmental stage the organism is in, affect its sensitivity to chloride toxicity. Finally, chemicals associated with chloride such as the cation in a chloride salt or additives can also be toxic.

Organisms also suffer sublethal effects from chloride salts. Many of these impacts result from chronic exposure. These impacts can also be influenced by the same factors discussed above that affect lethal toxicity of chloride salts.

Exposure to chloride salts has been shown to cause several types of sublethal impacts to plants. The most visible impacts are injuries to plant tissues. Depending on the type of plant and route of exposure, these can include wilting or browning of leaves and shoots, killing of buds, loss of leaves and needles, and dieback of tissues. Exposure to chloride salts can lead to reductions in growth resulting in plants of smaller size or biomass. Exposure to chloride can also impact plant reproduction through reducing flower production and seed germination. Finally, exposure to chloride salts can have adverse effects on plant physiological processes, such as causing nutritional deficiencies or reductions in photosynthesis.

Chloride salts can also cause sublethal impacts to animals. Exposure to chloride salts can induce changes in the metabolism rates of some animals that can increase energy requirements or lead to weight loss. Chloride exposure can affect animal growth and development. Slower growth, reduced growth, lengthened development times, altered sex ratios, and more developmental deformities have all been linked to exposure to high concentrations of chloride salts. Exposure to chloride salts can also affect animal reproduction. Reported impacts include reduced fertilization of eggs, increased age at first reproduction, reduced numbers of offspring produced, and inhibition of hatching of eggs. Exposure to chloride salts can also lead to altered behavior in animals. These alterations include changes to mobility such as slower swimming speeds, changes in feeding, and changes in habitats use. Finally, exposure to chloride salts can increase the susceptibility of some animals to parasites.

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[597] *P.H. Jones, B.A. Jeffrey, P.K. Watler, and H. Hutchon,* Environmental Impact of Road Salting—State of the Art*, Ontario Ministry of Transport and Communication, MTC No. RR237, 1986.*

3.3 IMPACTS OF CHLORIDE ON BIOLOGICAL COMMUNITIES

Background on Biological Communities

Biological communities consist of associations of species that occupy the same geographical area at the same time. For example, a pond community may consist of a variety of organisms including:

- Plants, bacteria, fungi, protists, and animals on the water surface
- Phytoplankton, zooplankton, bacteria, fungi, protists, invertebrates, and fish in the water column
- Plants, algae, bacteria, invertebrates, fungi, and protists on the sediment surface
- Bacteria, protists, fungi, and animals within the sediment

Any given community may be composed of a large number of species. This creates practical problems in studying communities. Because of this, many studies of communities examine portions of a community. These portions can be defined in different ways. Some consist of taxonomically related species, such as "the fish community." Others consist of species living in a single habitat type within a community, such as "the benthic community" or "the plankton community." Still other definitions consist of species that perform similar functions, such as "the herbivore community." Finally, another way to define a community is by simplified subsets of a community, such as interactions between a small number of species.

Community Measures

Several measures are used to describe and examine communities. Some of these measures describe the structure of the community. Species richness describes the number of species present in a community. In studies where organisms are not identified to the species level, this may also be presented as genus richness or taxon richness. Evenness describes how the relative numbers of individuals of each species compare to one another. High evenness is present when the relative abundances of all species are similar. Diversity measures the complexity of a community, and it takes both species richness and evenness into account. Communities with a larger number of species and more even abundances have higher diversity. Descriptions can also be made using biomass, which consists of the mass or weight of organisms in the community.

Communities can also be measured through community functions. Examples of this include primary production, secondary production, and processing of organic material. Primary production is defined as the formation of biomass resulting from photosynthesis. Secondary production consists of the formation of biomass by consumers. Processing of organic material refers to the breakdown of material produced by living organisms.

Community Structure

Community structure is a description of what species of organisms are present in a community, what their relative abundances are, and what relationships and interactions occur among these species. Several factors can influence community structure. Features of the abiotic environment such as climate, geography, and geology can exert strong effects on community structure. These environmental features partially determine which species can survive at a location. Their predictability may also influence the ability of a species to occupy an area. The heterogeneity of the environment determines the number of potential habitats that are present. More potential habitats create opportunities for species to be present within a community. Interactions among organisms also influence community structure. Adverse effects due to ecological processes such as interspecific competition, predation, and parasitism, as well as beneficial effects due to ecological processes such as mutualism, can influence the presence and abundance of species. Finally, random events, such as disturbances or colonization by other species, can affect community structure.

Factors that influence community structure may act by directly impacting some constituents of the community. For example, competition between zooplankton species for phytoplankton as a food resource may act to exclude some zooplankton species from the community. This may occur even though the excluded species could survive in the environment in the absence of its competitors. Other factors may influence community structure indirectly through mediation by other components of the community. For example, predation on large-bodied zooplankton by zooplanktivorous fish may allow phytoplankton populations to bloom, reducing the amount of light that reaches the lakebed, thereby reducing the abundance and biomass of macrophytes. In this example, the effect of the fish on macrophytes is indirect because it is mediated through the impacts of zooplankton on phytoplankton abundance and phytoplankton on light levels.

Some species may have stronger roles than others in creating or maintaining the structure of a community. Some species may act as habitat for other species. If they are not present, the species dependent on them will be unable to persist in the community. Aquatic macrophytes are an example of this. By creating physical structure in streams, ponds, and lakes macrophytes create habitat usable by some fish and macroinvertebrate species. Other species may maintain community structure through strong effects on other species. Piscivorous fish may act in this manner. By reducing the abundance of zooplanktivorous fish, they may allow the abundance of large zooplankton to increase, which acts to reduce the abundance of phytoplankton through grazing.

Food Webs

Food webs are one way to summarize and examine the structure of communities. They show links between different species of organisms. These linkages are based on trophic relationships—who eats whom and who eats what. Food webs may also incorporate some features of the abiotic environment such as nutrients or organic material that are required for some organisms to grow. Food webs present a conceptual approach to understanding species interactions and energy flow in ecological communities.

Presentations of food webs are often simplified relative to the number of species in a community. This simplification is partly a practical matter. It can be very difficult and require substantial effort to identify all the species present in a community and all the interactions among those species. At the same time, though, aggregating species into functional groups, such as species that use similar resources, can improve the ability to make generalizations regarding processes in a community.

Figure 3.17 shows an example of a food web in a pond. The figure shows individual food chains embedded within a network of feeding relationships. Producers such as algae and aquatic plants grow through photosynthesis based on the availability of light and nutrients. They are fed upon by a variety of consumers, ranging from zooplankton such as the water flea *Daphnia*, to snails, tadpoles, insects, and muskrat. Most of these are fed upon, in turn, by larger consumers such as fish. Large predators, such as herons, may feed on the fish. Excretions by these organisms and breakdown of dead organisms by scavengers such as crayfish and decomposers such as bacteria return nutrients to the system. While the figure is simplified, it presents a useful framework for examining this type of community.

Aquatic food webs are often connected to terrestrial food webs. For example, leaves shed by trees growing in riparian areas constitute a major source of energy and nutrients to food webs in small headwater streams. Bacteria and fungi grow on these leaves and serve as a source of food to many macroinvertebrates. This input of leaves ultimately supports higher trophic levels through food web interactions.

Effects of Chloride Tolerance Differences among Species in Communities

As discussed in the section on the effects of chloride salts on organisms in this Chapter, some species of organisms are more tolerant of chloride and chloride salts than other species. Among macroinvertebrates, for example, mayflies, stoneflies, and pulmonate snails are especially sensitive to salinity while beetles, dragonflies, damselflies, and some flies and crustaceans are more tolerant.[598] As the concentration of chloride salts and salinity increase, these differences in sensitivity to chloride can lead to changes in community composition and structure. At high enough chloride concentrations, sensitive species are likely to be lost from the community. While this could simply lead to increases in the abundance of tolerant species already present in the community, it could also lead to changes in the intensity of ecological processes such as competition or predation among the more tolerant species remaining in the community.[599] As a result,

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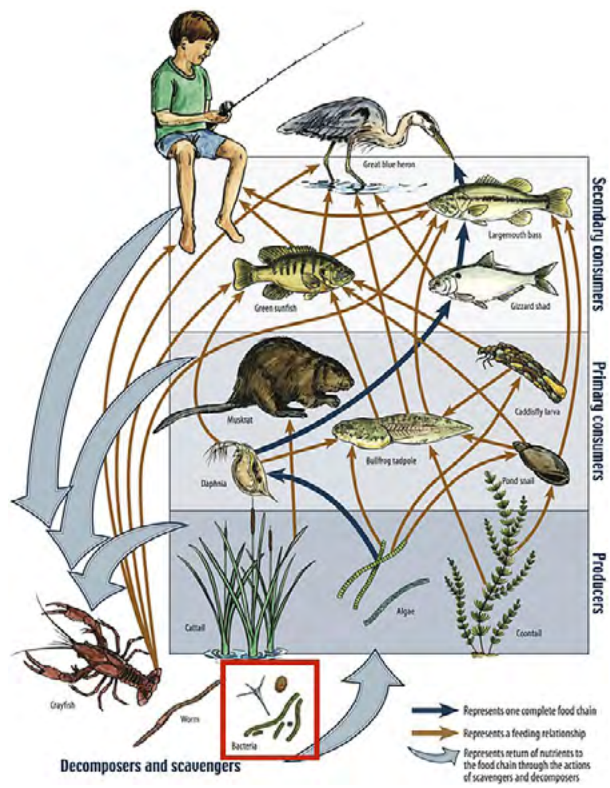
[598] *J.E. Dunlop, N. Horrigan, G. McGregor, B.J. Kefford, S. Choy, and R. Prasad, "Effect of Spatial Variation on Salinity Tolerance of Macroinvertebrates in Eastern Australia and Implications for Ecosystem Protection Trigger Values,"* Environmental Pollution*, 151:621-630, 2008.*

[599] *L. Blaustein and J.M. Chase, "Interactions Between Mosquito Larvae and Species that Share the Same Trophic Level,"* Annual Review of Entomology*, 52:489-507, 2007.*

the abundance of members of some tolerant species could increase, while the abundance of others could decline.

Differences in tolerance and changes in the intensity of ecological processes could also allow other tolerant species to invade and establish in the community. In some communities this could enhance colonization by alien exotic species while preventing the establishment of more sensitive native species.[600] Three examples illustrate this outcome. In the first example field surveys showed that the presence of exotic macroinvertebrate species was significantly associated with the highest salinity reaches of the Meurthe River in France.[601] In the second example, salinization of the River Weser in Germany led to several exotic crustacean species colonizing the river.[602] As salinity in the river increased, colonization proceeded upstream from the estuary. In the third example, a salt storage pile was operated adjacent to a bog in Indiana for 10 years.[603] The mean concentrations of chloride in water in the affected portion of the bog pile was 1,215 mg/l. The plant community in this area of the bog came to be dominated by invasive narrow-leaf cattail (*Typha angustifolia*). This cattail species can tolerate brackish water conditions, which may have contributed to its ability to invade this bog. In contrast, nearly all the endemic native plant species were absent from the affected portion of the bog.

Figure: 3.17
A Simplified Aquatic Food Web



Source: Missouri Department of Conservation

Effects of Chloride
Salts and Salinity on Community Composition

Several studies have examined the effect of chloride salts and salinity on the composition of communities. Most of these studies have examined impacts on aquatic communities. In addition, most have focused on only a portion of the community present at the study sites, such as plankton assemblages, periphyton assemblages, or macroinvertebrate assemblages. These studies also differ in the methodologies used. Some field studies have compared the composition of communities in waterbodies located in the same landscape that differed from one another in chloride concentration, salinity, or specific conductance. Other field studies have observed changes in community composition in a single waterbody as chloride concentrations increased. Experimental studies have taken a mesocosm approach and examined changes in community composition in response to manipulation of chloride concentration or salinity. Some of these experimental studies have reported thresholds of chloride concentration at which major changes in community composition were observed.

Effects of Chloride Salts on the Composition of Plankton Assemblages

Plankton communities consist of organisms that live in the water column that are unable to propel themselves against a current. Planktonic organisms are generally small. Many are microscopic and larger ones rarely exceed lengths of about 0.08 inch. Plankton communities are a resource base which supports higher trophic

[600] *U. Braukmann and D. Böhme, "Salt Pollution of the Middle and Lower Sections of the River Werra (Germany) and Its Impact on Benthic Macroinvertebrates,"* Limnologica*, 41:113-124, 2011.*

[601] *C. Piscart, J.-C. Moreteau, and J.-N. Beisel, "Biodiversity and Structure of Macroinvertebrate Communities Along a Small Permanent Salinity Gradient (Meurthe River, France),"* Hydrobiologia*, 551:227-236, 2005.*

[602] *J. Bäthe, "Decreasing Salinity in Werra and Weser (Germany): Reactions of the Phytoplankton and Macrozoobenthos,"* Limnologica*, 27:111-119, 1997.*

[603] *Wilcox 1986,* op. cit.

levels and provides ecosystem services such as primary production, decomposition, and nutrient cycling. Plankton in freshwater systems are composed of diverse assemblages of algal phytoplankton, zooplankton, bacteria, fungi, and protists such as ciliates and flagellates.

Several studies have found that increases in salinity can reduce the number of phytoplankton present.[604] For example, a field study compared the phytoplankton assemblages in the forebays and pond areas of two stormwater ponds in Ontario.[605] In Harding Pond, specific conductance in the forebay was 1,150 μS/cm, while specific conductance was only 520 μS/cm in the pond. The phytoplankton assemblage in the forebay consisted of 10 genera, but a species of *Euglena*, a euglenoid flagellate, accounted for about 89 percent of the phytoplankton biovolume, a measure of phytoplankton biomass. The phytoplankton assemblage in the pond consisted of 16 genera including green algae, cryptomonad flagellates, diatoms, and euglenoid flagellates. *Euglena* accounted for only 56 percent of the biovolume of phytoplankton. The concentration of phytoplankton biovolume in the pond was about 25 percent of that found in the forebay. This study also looked at a second stormwater pond. In Rouge Pond, specific conductance in the forebay was 2,950 μS/cm, while specific conductance was 1,900 μS/cm in the pond. While similar differences in specific conductance were observed in the forebay and the pond, no differences were observed between the forebay and pond phytoplankton assemblages. The different response observed in the phytoplankton assemblage in Rouge Pond may be the result of the much higher levels of specific conductance in this pond.

A study examining plankton assemblages in four urban lakes exposed to road salt in Quebec City, Canada showed that differences in the taxonomic composition of both bacterial and eukaryotic plankton was explained by differences in the concentrations of chloride and total nitrogen under both ice-covered and open water conditions.[606] The plankton assemblages in lakes with the lowest levels of salinization consisted mostly of chrysophyte flagellates and ciliates, while more salinized lakes had higher abundance of dinoflagellates, cryptomonad flagellates, and haptophyte flagellates. Differences were also seen among the bacterial assemblages that were present based on the degree of salinization.

A mesocosm experiment examined the effects of chloride concentrations on the plankton assemblage from a lake with low chloride concentrations.[607] Ambient chloride concentrations in Lake Croche in Quebec, Canada are normally about 0.27 mg/l. Plankton from the lake was placed into 21 mesocosms to which sodium chloride was added at chloride concentrations ranging between 0.27 mg/l and 1,400 mg/l. These mesocosms were incubated within the lake for six weeks. Several changes in community composition occurred over the chloride gradient. While total phytoplankton biomass did not change with chloride concentration, a major shift in phytoplankton composition was observed. At chloride concentrations below 185 mg/l, green algae and cryptomonad flagellates were the dominant groups of phytoplankton present. At chloride concentrations equal to and above 185 mg/l, the assemblage shifted to one dominated by chrysophyte flagellates with some diatoms and xanthrophyte algae. This change reduced the value of the phytoplankton assemblage as a food resource for zooplankton.[608] At chloride concentrations above 640 mg/l, only phytoplankton were present in the mesocosms.

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[604] *See for example: Batterton and Baalen 1971,* op. cit.*; L.M. Kipriyanova, N.I. Yermolaeva, D.M. Bezmaternykh, S.Y. Dvurechenskaya, and E.Y. Mitrofanova, "Changes in the Biota of Chany Lake Along a Salinity Gradient,"* Hydrobiologia*, 576:83-93, 2007; and E. Coring and J. Bäthe, "Effects of Reduced Salt Concentrations on Plant Communities in the River Werra (Germany),"* Limnologica*, 41:134-142, 2011.*

[605] *D.D. Olding, "Algal Communities as a Biological Indicator of Stormwater Management Pond Performance and Function,"* Water Quality Research Journal of Canada*, 35:489-503, 2000.*

[606] *I.B. Fournier, C. Lovejoy, and W.F. Vincent, "Changes in Community Structure of Under-Ice and Open-Water Microbiomes in Urban Lakes Exposed to Road Salts,"* Frontiers in Microbiology, *12:660719, 2021.*

[607] *L. Astorg, J.-C. Gagnon, C.S. Lazar, and A.M. Derry, "Effects of Freshwater Salinization on a Salt-Naïve Planktonic Eukaryote Community,"* Limnology and Oceanography Letters*, 8:38-47, 2023.*

[608] *S. Taipale, U. Strandberg, E. Peltomaa, A.W.E. Galloway, A. Ojala, and M.T. Brett, "Fatty Acid Composition as Biomarkers in Freshwater Microalgae: Analysis of 37 Strains of Microalgae in 22 Genera and in Seven Classes,"* Aquatic Microbial Ecology*, 71:165-178, 2013.*

Changes in other components of the plankton also occurred in the Lake Croche mesocosms with increasing chloride concentration.[609] Zooplankton, including cladocerans, copepod, and rotifers disappeared at chloride concentrations above about 40 mg/l. Ciliates were common at chloride concentrations below 185 mg/l but decreased in abundance above this chloride level. At chloride concentrations between 185 mg/l and 640 mg/l fungi dominated the plankton but they were not present at concentrations above 640 mg/l.

Effects of Chloride Salts on the Composition of Periphyton Assemblages

Periphyton consists of organisms growing on submerged surfaces, such as rock and plants. It is composed of a complex mixture of organisms and their secretions. Organisms making up the periphyton include bacteria, cyanobacteria, eukaryotic algae, microinvertebrates, and protozoa such as ciliates, flagellates, and amoeboid protists. Major algal components often include diatoms and green algae. Periphyton can serve as an important food resource for other organisms including some species of macroinvertebrates, tadpoles, and fish.

A field study compared the periphyton assemblages in the forebays and pond areas of two stormwater ponds in Ontario.[610] In Harding Pond, specific conductance in the forebay was 1,150 µS/cm, while specific conductance was only 520 µS/cm in the pond. The periphyton assemblage in the forebay consisted of nine genera, mostly diatoms and a species of the green alga *Oedogonium*. The periphyton assemblage in the pond consisted of eight genera consisting mostly of green algae, including the species *Protococcus viride*. In Rouge Pond, specific conductance in the forebay was 2,950 µS/cm, while specific conductance was 1,900 µS/cm in the pond. The periphyton assemblage in the forebay consisted of five genera, with diatoms accounting for about 95 percent of the biovolume. The periphyton assemblage in the pond consisted of 17 genera, mostly green algae and cyanobacteria species. The concentration of biovolume in the pond was almost nine times that of the forebay. The study noted that the two ponds treated stormwater from drainage areas with different land uses. The area draining to Harding Pond consisted mostly of residential developments. Stormwater entering this pond contained high concentrations of nutrients, which might explain why periphyton species richness was similar between the forebay and pond area. The area draining to Rouge Pond consisted of industrial development. Stormwater entering this pond contained much lower nutrient concentrations.

A field study sampled the periphyton of 41 streams across a chloride gradient in south-central Ontario and examined the composition of the periphytic diatom assemblages in the streams.[611] Chloride concentrations in the streams ranged between 5 mg/l and 502 mg/l. While the study found a strong association between species composition and specific conductance, diversity measures did not correlate with chloride concentration. This suggests that as chloride concentration increased across the streams, sensitive species were replaced by more tolerant species, resulting in little change in the diversity measures. This is supported by the fact that several species disappeared entirely as the concentration of chloride increased, and the abundances of several species were correlated with chloride concentration. Taxonomic indicator analysis showed that the greatest change in the structure of the diatom assemblages occurred over chloride concentrations ranging between 15 mg/l and 35 mg/l. Above 35 mg/l the diatom assemblage changes were more gradual.

Effects of Chloride Salts on the Composition of Macroinvertebrate Assemblages

Macroinvertebrates were previously described in the section on effects of chloride salts on freshwater organisms. As noted in that section, some groups of these animals are more sensitive to impacts from chloride salts than others. These differences in sensitivity can lead to variations in the composition of macroinvertebrate assemblages in aquatic environments with different chloride concentrations.

A field study in southeastern Ontario that examined 20 groundwater fed streams with average chloride concentrations ranging between 8 mg/l and 1,149 mg/l found differences in the composition of macroinvertebrate assemblages that were related to chloride concentration.[612] Fly species such as crane flies and biting midges were found at sites with higher chloride concentrations. Amphipods, especially the species *Gammarus pseudolimneaus*, and flatworms were found only in streams with low chloride concentrations.

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[609] *Astorg et al. 2023,* op. cit.

[610] *Olding 2000,* op. cit.

[611] *Porter-Goff et al. 2013,* op. cit.

[612] *D.D. Williams, N.E. Williams, and Y. Cao, "Spatial Differences in Macroinvertebrate Community Structure in Springs in Southeastern Ontario in Relation to Their Chemical and Physical Environment,"* Canadian Journal of Zoology, *75:1,404-1,414, 1997.*

Another field study surveyed macroinvertebrates assemblages at 107 sampling sites on rivers in eastern Spain and found differences in the assemblages that were related to salinity and specific conductance.[613] As salinity and specific conductance increased along the salinity gradient, the percentage of mayflies, stoneflies, and caddisflies in the assemblage decreased. At the same time, the percentages of beetles, true bugs, dragonflies, and damselflies in the assemblage increased. As previously noted, mayflies and stoneflies are relatively sensitive to effects from chloride. Macroinvertebrate assemblages at salinized sites were dominated by species with short life spans, especially fly species such as midges, biting midges, black flies, and shore flies.

Another study of the effects of salinity on stream macroinvertebrate assemblages found shifts in assemblage composition related to salinity.[614] Shifts in assemblage membership from sensitive taxa to tolerant taxa were observed to occur at salinities between 544 mg/l and 680 mg/l. This corresponded to a specific conductance range of 800 µS/cm to 1,000 µS/cm. In riffle habitats, shifts were seen to occur at a salinity of 440 mg/l which corresponded to a specific conductance of 300 µS/cm.

Effects of Chloride Salts and Salinity on Biodiversity

Biodiversity describes the variety of living organisms. There are several different ways of measuring it, each of which captures an important component contributing to total biodiversity. Taxonomic diversity, for example, examines the different types of organisms that are present. It can be evaluated at the species level, the genus level, or some other level of biological organization. As another example, trait diversity examines the different types of traits present in organisms. Traits may include mode of feeding, where or how reproduction occurs, and how respiration occurs. Studies have examined the effects of chloride salts and salinity on both taxonomic and trait biodiversity.

Effects of Chloride Salts and Salinity on Taxonomic Diversity

Several studies have examined the effect of chloride salts and salinity on taxonomic diversity in aquatic communities. In combination, these studies address a range of organisms. Many studies analyze their results using diversity indices and measures of species richness. Interpretation of these indices requires some caution. If the loss of sensitive species from a community due to increased chloride concentration is accompanied by the community gaining more tolerant species, aggregate metrics such as species richness or diversity indices might not change.[615]

A paleolimological study examined the impact of increasing salinity on planktonic and periphytic diatoms following construction of a salt storage area adjacent to Fonda Lake near Brighton, Michigan.[616] The diversity and evenness of the diatom assemblage decreased following construction of the storage facility. Over the same time period the abundance of salt-loving diatom species increased. These trends peaked at about the time that the storage area was modified to reduce salt loading to the lake. Following modifications to the storage area, the levels of diatom species diversity and evenness increased, and the abundance of salt-loving species decreased. A second study that examined the same Fonda Lake sediment core found that changes occurred in the assemblage of scaled chrysophyte flagellates that mirrored those seen in the diatom assemblage.[617]

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[613] *C. Gutiérrez-Cánovas, D. Sánchex-Fernández, M. Cañedo-Argülles, A. Millán, J. Velasco, R. Acosta, P. Fortuño, N. Otero, A. Soler, and N. Bonada, "Do All Roads Lead To Rome? Exploring Community Trajectories in Response to Anthropogenic Salinization and Dilution of Rivers,"* Philosophical Transactions of the Royal Society Series B, *374:20180009, 2018.*

[614] *N. Horrigan, S. Choy, J. Marshall, and F. Recknagel, "Response of Stream Macroinvertebrates to Changes in Salinity and the Development of a Salinity Index,"* Marine and Freshwater Research*, 56:825-833, 2005.*

[615] *A.M. Wallace and R.G. Biastoch, "Detecting Changes in the Benthic Invertebrate Community in Response to Increasing Chloride in Streams in Toronto, Canada,"* Freshwater Science, *35:353-363, 2016.*

[616] *M.L Tuchman, E.F. Stoermer, and H.J. Carney, "Effects of Increased Salinity on the Diatom Assemblage of Fonda Lake, Michigan,"* Hydrobiologia*, 109:179-188, 1984.*

[617] *B.A. Zeeb and J.P. Smol, "Paleolimnological Investigation or the Effects of Road Salt Seepage on Scaled Chrysophyte Flagellates in Fonda Lake, Michigan,"* Journal of Paleolimnology*, 5:263-266, 1991.*

A field experiment found that continuous exposure to elevated concentrations of sodium chloride for periods as short as one week can result in significant changes in periphyton assemblages.[618] Sodium chloride was added to water at four locations along Heyworth Stream in Heyworth, Quebec to maintain instream chloride concentrations at 1,000 mg/l along a reach of the stream for 10 weeks. Periphyton was sampled weekly using artificial substrate samplers. The diversity of algae on the samplers was consistently lower at sites with high chloride concentration than it was at control sites. Some of reduction of diversity with higher chloride concentration may have been related to some diatom species forming auxospores, a resting stage whose formation is generally triggered by environmental stress. The standing crop of algae on the samplers was also lower at sites with high chloride concentrations. High salt concentrations also affected other groups of periphytic organisms. Bacterial diversity was higher at sites with high chloride concentration than at controls. This was attributed to reductions in grazing pressure on bacteria due to reduced numbers of flagellates, ciliates, and other protozoa that graze on bacteria. Finally, the incidence of parasitism on diatoms by fungi was lower at sites with high chloride concentrations. This was likely due to elevated concentrations of chloride inhibiting fungal growth. Other studies have noted decreases in the incidence of fungal infections at elevated chloride concentrations,[619] although some others have noted that brief exposures to high salinity may increase the rate of infection of embryonic amphibians by lethal water mold.[620]

Chloride has also been associated with reductions in zooplankton diversity. A mesocosm study observed that reductions in zooplankton abundance and species richness occurred at chloride concentrations of 250 mg/l.[621] The study also found that in the assemblage from one lake, salt additions drove zooplankton species composition toward dominance by cladoceran species normally found in the littoral area.

Increased chloride concentrations and salinity have been associated with changes in stream macroinvertebrate diversity. One study that noted a dramatic increase in chloride concentration downstream of a heavily salted highway observed a significant decrease in the diversity of aquatic insects inhabiting artificial substrate samplers placed downstream of the highway.[622] Several other field studies have observed that macroinvertebrate species richness decreased with higher specific conductance.[623] One of these studies observed significant decreases in macroinvertebrate species richness occurring at specific conductance above 1,500 μS/cm.[624] This study also noted that smaller increases in salinity sometimes resulted in increases in overall macroinvertebrate species richness; however, species richness of mayflies, stoneflies, and caddisflies (EPT species richness), decreased with increasing salinity. Since high EPT species richness is usually interpreted to indicate better water quality, this result suggests a community response reflecting a decline in water quality. A flow-through mesocosm study found that short-term exposures to chloride can have large effects on stream macroinvertebrate assemblages.[625] Benthic macroinvertebrate assemblages in these mesocosms were exposed to pulses of sodium chloride lasting 24 to 72 hours, with different microcosms being exposed

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[618] *M.D. Dickman and M.B. Gochnauer, "Impact of Sodium Chloride on the Microbiota of a Small Stream,"* Environmental Pollution*, 17:109-126, 1978.*

[619] *See, for example: L.A. Kszos, J.D. Winter, and T.A. Storch, "Toxicity of Chautauqua Lake Bridge Runoff to Young-of-the-Year Sunfish (*Lepomis macrochirus*),"* Bulletin of Environmental Contamination and Toxicology*, 45:923-930, 1990; J. Rantamaki, L. Cerenius, and K. Soderhall, "Prevention of Transmission of the Crayfish Plague Fungus (*Aphanomyces astaci*) to the Freshwater Crayfish* Astacus astacus *by Treatment with* $MgCl_2$*,"* Aquaculture*, 104:11-18, 1992.*

[620] *N.E. Karraker and G.R. Ruthig, "Effect of Road Deicing Salt on the Susceptibility of Amphibian Embryos to Infection by Water Molds,"* Environmental Research*, 109:40-45, 2009.*

[621] *J.S. Sinclair and S.E. Arnott, "Local Context and Connectivity Determine the Response of Zooplankton Communities to Salt Contamination,"* Freshwater Biology*, 63:1,273-1,286, 2018.*

[622] *C.L. Demers and R.W. Sage, Jr., "Effects of Road Deicing Salt on Chloride Levels in Four Adirondack Streams,"* Water, Air, and Soil Pollution*, 49:369-373 1990.*

[623] *A.M. Pinder, S.A. Halse, J.M. McRae, and R.J. Shiel, "Occurrence of Aquatic Invertebrates of the Wheatbelt Region of Western Australia in Relation to Salinity,"* Hydrobiologia*, 543:1-24, 2005; D. Böhme, "Evaluation of Brine Discharge to Rivers and Streams: Methodology of Rapid Impact Assessment,"* Limnologica*, 41:80-89, 2011; B.J. Kefford, R. Marchant, R.B. Schäfer, L. Metzeling, J.E. Dunlop, S.C. Choy, and P. Goonan, " The Definition of Species Richness Used by Species Sensitivity Distributions Approximates Observed Effects of Salinity on Stream Macroinvertebrates,"* Environmental Pollution*, 159:302-310, 2011.*

[624] *Kefford et al. 2011*, op. cit.

[625] *Cañedo-Argüelles et al. 2012*, op. cit.

to different sodium chloride concentrations. At higher chloride concentrations, macroinvertebrate diversity, as measured by the Shannon diversity index, decreased after 24 hours of exposure and taxon richness and EPT richness decreased after 72 hours of exposure. The most sensitive species were lost from the assemblages at higher chloride levels. The authors suggested a specific conductance threshold of 5,000 µS/cm at which short-term exposure to salt has a significant effect on macroinvertebrate community structure.

Chloride concentration can also affect the diversity of vertebrate assemblages. A field study found that amphibian species richness decreased with chloride concentration in a survey of 26 ponds in Nova Scotia.[626] Ponds that were near roads had chloride concentrations of around 400 mg/l. These ponds typically contained only one or two amphibian species. Ponds in a wood lot away from roads had chloride concentrations below 50 mg/l and they typically contained three to six amphibian species. Chloride can also affect the diversity of fish assemblages. Examination of field data from the State of Maryland's biological stream surveys showed that fish assemblage diversity can be reduced at chloride concentrations between 33 mg/l and 108 mg/l.[627]

Finally, chloride concentrations can affect the diversity of plants in wetlands. A study of an acid peat-rich fen that received inputs of deicing salts from the Massachusetts turnpike found that plant species richness and total plant cover were lower in pots where soil pore water chloride concentrations were greater than 54 mg/l.[628]

Effects on of Chloride Salts and Salinity on Trait Diversity

Increases in concentration of chloride salts and salinity have also been associated with changes in the diversity of traits present in a community or assemblage. This has been studied mostly in macroinvertebrate assemblages. A three-year field study that examined biological traits in macroinvertebrates at 15 sites along the River Werra in Germany found the dominant traits at sites with high specific conductance were different from those at sites with low specific conductance.[629] This study found that macroinvertebrates at sites with higher specific conductance tended to incubate their eggs within their bodies, exchange gases through gills, and reproduce several times a year, while those at sites with lower specific conductance tended to lay their eggs in clutches, exchange gases through their body walls, and reproduce once a year. In a second study, surveys of macroinvertebrates at 107 sites along streams and rivers in eastern Spain found that macroinvertebrate assemblages at salinized sites were dominated by species that had short life spans, incubated their eggs within their bodies or laid their eggs outside of water, conducted gas exchange using air through a variety of means, and reproduced several times a year.[630] Other macroinvertebrate traits associated with higher salinity include species having limited dispersal abilities and feeding through predation, deposit feeding, or filter feeding as opposed to grazing on periphyton or shredding leaves.[631]

Effects of Chloride Salts and Salinity on Interspecific Competition

Interspecific competition is an interaction that can occur between two or more species that require a resource that is in limited supply. Over time one species will obtain more of the resource and be able to grow more quickly, either through obtaining the resource more efficiently or interfering with the ability of the other species to obtain the resource. The competitive abilities of species are based on their traits and physiologies and how these are affected by their environment. Over time, a superior competitor can exclude a poorer competitor from an area; however, disturbance to and short-term changes in the environment may

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[626] *Collins and Russell 2009,* op. cit.

[627] *R.P. Morgan, K.M.L. Kline, M.J. Kline, S.F. Cushman, M.T. Sell, R.E. Weitzell, Jr., and J.B. Churchill, "Stream Conductivity: Relationships to Land Use, Chloride, and Fishes in Maryland Streams,"* North American Journal of Fisheries Management, *32:941-952, 2012.*

[628] *J.A. Richburg, W.A. Patterson, and F. Lowenstein, "Effects of Road Salt and* Phragmites australis *Invasion on the Vegetation of a Western Massachusetts Calcareous Lake Basin Fen,"* Wetlands*, 21:247-255, 2001.*

[629] *Gutiérrez-Cánovas et al. 2018,* op. cit.

[630] *Scozs et al. 2014,* op. cit.

[631] *N.A. Marshall, and P.C.E. Bailey, "Impact of Secondary Salinization on Freshwater Ecosystems: Effects of Contrasting, Experimental, Short-Term Releases of Saline Wastewater on Macroinvertebrates in a Lowland Stream,"* Marine and Freshwater Research, *55:509-523, 2004; Piscart et al. 2006;* op. cit.*; B.J. Kefford, R.B. Schäfer, and L. Metzeling, "Risk Assessment of Salinity and Turbidity in Victoria (Australia) to Stream Insects' Community Structure Does Not Always Protect Functional Traits,"* Science of the Total Environment*, 415:61-68, 2012.*

alter the relative competitive abilities of species, allowing them to coexist. In addition, coexistence may also occur when species compete for more than one resource that could potentially limit their growth.[632]

Increases in concentrations of chloride salts and salinity may change competitive relationships between species through favoring more physiologically tolerant species.[633] In particular, differences in how the energetic costs of osmoregulation for each species changes with increasing salinity could alter species relative competitive abilities.[634] A few experiments have examined the effects of chloride levels and salinity on interspecific competition.

Increased salinity changed the competitive outcome between two planktonic green algal species in 96-hour competition assays.[635] In single species tests at low salinity, *Raphidocelis subcapitata* grew more quickly than *Chlorella vulgaris*. As salinity increased, *R. subcapitata's* growth rate decreased more rapidly than *C. vulgaris'*. At higher salinity, *C. vulgaris* outcompeted *R. subcapitata* in combined tests.

Similar results were observed in competition experiments with two zooplankton species.[636] At sodium chloride concentrations below 750 mg/l, the water flea *Daphnia galeata* outcompeted the water flea *Simocephalus vetolus* in competition assays. At higher sodium chloride concentrations, *D. galeata's* growth rate dropped below that of *S. vetolus.* Over the course of the experiment at these concentrations, *S. vetolus* was able to outcompete *D. galeata*.

The effects of chloride salts on competition can be complex, especially when several species are potentially competing for the same resources or when some of the competing species could potentially prey on other competing species. A series of mesocosm experiments examined the effects of chloride salts on both competitive and predatory relationships between large zooplankton, aquatic insect larvae, and tadpoles.[637] In this experiment, the researchers set up mesocosms with different concentrations of road salts. The salts used consisted mostly of sodium chloride. The mesocosms also contained large zooplankton and tadpoles. They were open to the air, allowing aquatic insects such as mosquitoes, midges, and shore flies to lay their eggs in the mesocosm.

For most of the invertebrate taxa in the mesocosms, the absolute number of individuals present decreased with salt concentration; however, the relative abundance of some taxa increased over some ranges of salt concentration. At low salt concentrations, large zooplankton consisting mostly of cladocerans dominated the invertebrate assemblages, accounting for 83 to 97 percent of the invertebrates present. This changed at higher salt concentrations. Mosquito larvae dominated the invertebrate assemblage at salt concentrations between 1,000 mg/l and 4,000 mg/l, representing over 80 percent of the invertebrates present. Midge larvae dominated at salt concentrations between 4,000 mg/l and 6,000 mg/l. Shore flies were the only invertebrates present at salt concentrations above 6,000 mg/l.

Additional experiments in this study showed that egg laying by mosquitoes was not affected by the concentration of salt in the mesocosms. It was affected by the presence of tadpoles or cladocerans, potential competitors for food with mosquito larvae. Mosquitoes laid fewer clutches of eggs in mesocosms containing cladoceran zooplankton than in those containing no invertebrates. Also, clutches laid in mesocosms containing tadpoles contained fewer eggs than those laid in mesocosms containing no invertebrates. This suggests that adult mosquitoes chose egg laying sites based on the presence or absence of other species that are potential competitors with their larvae for resources.

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[632] *D. Tilman,* Resource Competition and Community Structure, *Princeton University Press, Princeton, New Jersey, 1982.*

[633] *Busse et al. 1999,* op. cit.; *S.S.S. Sarma, B. Elguea-Sánchez, and S. Nandini, "Effect of Salinity on Competition Between the Rotifers* Brachionus rotundiformis *Tschugunoff and* Hexarthra jenkinae *(De Beauchamp) (Rotifera),"* Hydrobiolgia*, 474:183-188, 2002.*

[634] *Coring and Bäthe 2011,* op. cit.

[635] *C. Venâncio, E. Anselmo, A.M.V.M. Soares, and I. Lopes, "Does Increased Salinity Influence the Competitive Outcome of Two Producer Species?"* Environmental Science and Pollution Research, *24:5,888-5,897, 2017.*

[636] *C. Loureiro, J.L. Pereira, M.A. Pedrosa, F. Gonçalves, and B.B. Castro, "Competitive Outcome of* Daphnia-Simocephalus *Experimental Microcosms: Salinity Versus Priority Effects,"* PLoS One*, 8:e70572, 2013.*

[637] *J.W. Petranka and E.J. Doyle, "Effects of Road Salts on the Composition of Seasonal Pond Communities: Can the Use of Road Salts Enhance Mosquito Recruitment?"* Aquatic Ecology*, 44:155-166, 2010.*

The authors of the study concluded that the differences in taxa present in mesocosms at different salt concentrations occurred due to a combination of salt intolerance, competition, and predation. The increase in the relative abundance of mosquito larvae occurred at the same salt concentration at which cladoceran zooplankton declined. Both mosquito larvae and cladocerans feed on phytoplankton. At low salt concentrations, zooplankton were able to outcompete mosquitoes for this food and mosquitoes were rare in these mesocosms. The greater sensitivity of zooplankton to salt altered the competitive balance between them and the mosquitoes.

Similarly, the increase in the relative abundance of midge larvae occurred at the same salt concentration at which tadpole survival and growth rates are reduced. Both tadpoles and midges feed on detritus, but tadpoles are also able to feed on midge larvae. Depression of tadpole performance at higher salt concentrations released the midges from the stresses of both competition and predation, allowing them to dominate the mesocosms at higher salt concentrations.

Effects of Chloride Salts and Salinity on Food Web Interactions

As previously described, food webs show trophic linkages between different species in a community. These linkages can influence the abundance of different species in the community. Some influences move upward through the food web from lower levels such as from producers or primary consumers (bottom-up effects). In order to persist in a community, a consumer species needs an adequate supply of food. This may be provided either by the presence of a large standing crop or by a high production rate of food organisms or nutrients. Increases in either the standing crop, the rate of production of the food organisms, or nutrients can result in increases in the abundance or biomass of the consumer species in the community. The converse is true as well, as decreases in the standing crop, the production rate of the food organisms, or nutrients can result in lower abundance or biomass of the consumer species.

Other influences move downward through the food web from higher levels such as top predators (top-down effects). An increase in the abundance of a top predator may reduce the abundance of its food species. For example, an increase in the abundance of piscivorous fish could reduce the abundance of zooplanktivorous fish. This could reduce feeding pressure exerted by the second species on its food leading to an increase in the abundance of the third species. In this example the result might be an increase in the abundance of zooplankton.[638]

Increases in the concentration of chloride salts and salinity may change the structure of food webs by having a greater effect on some species more than others. The direct effects of chloride or salinity on some species may lead to indirect effects on other species through changes in the strength of food web linkages. An example of food web linkage is illustrated in the complete food chain shown in Figure 3.17. As noted earlier in this Chapter, zooplankton such as *Daphnia* are generally more sensitive to toxicity from chloride salts than fish or algae. Higher chloride salt concentrations could result in a decrease in *Daphnia* abundance and biomass. This decrease could reduce the amount of grazing on planktonic algae, resulting in an increase in phytoplankton abundance and biomass. Lower *Daphnia* abundance and biomass also reduces the food resources for small, zooplanktivorous fish like gizzard shad, causing a decrease in the abundance and biomass of these fish. Similarly, a reduction in the abundance and biomass of smaller fish reduces the food resources available to larger, piscivorous fish like largemouth bass. While the effect of chloride on *Daphnia* in this example is direct, the effect on other species is indirect and mediated through reductions in the availability of *Daphnia* biomass. An example of this food web effect was seen in Lake Michigan where a reduction in the abundance and diversity of zooplankton led to a reduction in fish recruitment and growth.[639]

[638] *J.M. Dettmers, M.J. Raffenberg, and A.K. Weis, "Exploring Zooplankton Changes in Southern Lake Michigan: Implications for Yellow Perch Recruitment,"* Journal of Great Lakes Research*, 29:35-364, 2003.*

[639] Ibid.

One study described a full set of potential effects that might occur in the food webs of lakes in response to contamination by road salt.[640] This study suggested that several food web linkages could be indirectly affected by increasing concentrations of chloride salts. Potential effects include:

1. Road salt contamination reduces the abundance and diversity of zooplankton

2. Reduced grazing by zooplankton leads to algal blooms which are exacerbated by the release of phosphorus from sediment in the lakebed (see No. 5 below)

3. Shading of the lakebed by algal blooms combines with chloride toxicity effects to reduce primary production by benthic algae and macrophytes

4. Road salt causes a density gradient which inhibits lake mixing and causes oxygen depletion in deep water

5. Oxygen depletion in deep water leads to the release of phosphorus from the sediment

6. Reduced benthic primary production leads to reductions in macroinvertebrate production

7. Reduced abundance and biomass of zooplankton and macroinvertebrates leads to reduced fish recruitment

8. Reduced fish recruitment leads to reductions in the abundance and biomass of piscivorous fish

9. Shading due to phytoplankton blooms reduce the foraging success of visual predators such as fish

Several studies have reported food web effects with increases in concentrations of chloride or salinity. These include both field and experimental studies. Most of these studies examined only a small number of linkages within a food web.

Several field studies show food web effects in response to changes in the concentration of chloride salts or salinity. A study on solar evaporation ponds in the Mojave Desert found that increased salinity favored a predatory water boatman (*Trichocorixa reticulata*) that feeds on algae-eating brine shrimp (*Artemia franciscana*).[641] The reductions in brine shrimp abundance due to increased feeding by the water boatman led to an increase in algal biomass in the ponds. Similarly, a survey of eight stormwater ponds near Baltimore, Maryland over spring and early summer showed differences in the sizes of phytoplankton and zooplankton assemblages that were related to specific conductance.[642] Ponds with low and moderate levels of specific conductance had higher abundance of zooplankton and lower biomass of phytoplankton than ponds with higher levels of specific conductance. The authors suggested that the negative effects of salt on zooplankton reduced grazing pressure on the phytoplankton. Studies on Third Sister Lake in Ann Arbor, Michigan found that the abundance of large-bodied zooplankton decreased as the concentration of chloride in the lake increased.[643] This reduced the amount of grazing on phytoplankton led to increases in phytoplankton abundance.

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[640] *Hintz and Relyea 2019,* op. cit.

[641] *D. Herbst, "Salinity Controls on Trophic Interactions among Invertebrates and Algae of Solar Evaporation Ponds in the Mojave Desert and Relation to Shorebird Foraging and Selenium Risk,"* Wetlands*, 26:475-485, 2006.*

[642] *R.J. Van Meter, C.M. Swan, and J.W. Snodgrass, "Salinization Alters Ecosystem Structure in Urban Stormwater Detentio Ponds,"* Urban Ecosystems*, doi: 10.1007/s1 1252-011-0180-9, 2011.*

[643] *T.B. Bridgeman, C.D. Wallace, G.S. Carter, R. Carvajal, L.C. Schiesari, S. Aslam, E. Cloyd, D. Elder, A. Field, K.L. Yurista, and G.W. Kling, "A Limnological Survey of Third Sister Lake, Michigan with Historical Comparisons,"* Lake and Reservoir Management*, 16:253-267, 2000; K.E. Judd, H.E. Adams, N.S. Bosch, J.M. Kostrzewski, C.E. Scott, B.M. Schultz, D.H. Wang, and G.W. Kling, "A Case History: Effects of Mixing Regime on Nutrient Dynamics and Community Structure in Third Sister Lake, Michigan During Late Winter and Early Spring 2003,"* Lake and Reservoir Management*, 21: 316-329, 2005.*

Experimental studies have also shown food web responses to changes in the concentration of chloride salts. A six-week mesocosm experiment exposed the plankton community from Convict Lake, an oligotrophic lake in California, to chloride concentrations ranging between one and 2,900 mg/l.[644] Chloride concentrations in this lake are normally less than two mg/l, but calcium concentrations are relatively high. Zooplankton biomass initially increased with chloride concentration; however, at chloride concentrations above 481 mg/l, zooplankton biomass decreased with increasing chloride concentration. The initial increase in biomass may have been due to the animals requiring a small amount of sodium in their diet. Alternatively, the presence of high calcium concentrations may have mitigated the toxic effects of sodium chloride at lower chloride concentrations. Zooplankton species richness and average body size decreased with rising chloride concentration. This partially reflects shifts in the zooplankton species that were present. Ostracods became more common at higher chloride concentrations and were the only zooplankton in the mesocosms at chloride concentrations above 1,200 mg/l. The phytoplankton assemblage showed the opposite response to chloride concentration. At chloride concentrations below 500 mg/l, phytoplankton biomass decreased with increasing chloride concentration. Phytoplankton biomass remained stable at chloride concentrations between 500 mg/l and 900 mg/l. At concentrations above 900 mg/l, phytoplankton biomass increased with increasing chloride concentration. This experiment shows strong food web effects. The inverse response of zooplankton and phytoplankton suggests that the main effect of chloride salts on phytoplankton occurred through changes in grazing pressure by zooplankton.

A 78-day mesocosm experiment examined the effect of chloride on lake organisms including phytoplankton, periphyton, filamentous algae, zooplankton, and macroinvertebrates.[645] The abundance of zooplankton and macroinvertebrates decreased as chloride concentration increased. At the same time, biomass of phytoplankton and periphyton increased due to the reduced grazing by herbivores.

Effects of Interactions Between Chloride Salts and Other Factors

The structure of biological communities can be influenced by numerous factors. These factors often operate simultaneously which can make it difficult to evaluate the importance of impacts from a single factor, such as increases in the concentration of chloride salts or salinity. In addition, there may be interactions between factors leading to different or more severe outcomes than would result from the effects of a single factor. Experimental studies have examined the interactions between the concentration of chloride salts and two other factors—nutrient concentrations and the presence of predators.

Interactions Between Chloride Salts and Nutrients

A six-week experiment exposed the plankton community taken from Long Lake in Ontario, Canada to different combinations of chloride and phosphorus concentrations.[646] Plankton from the lake were placed into mesocosms with chloride concentrations ranging between 0.41 mg/l, the ambient concentration found in the lake, and 1,500 mg/l. Two nutrient treatments were established in the mesocosms. In one treatment, phosphorus was added to bring the concentration to 0.031 mg/l. Nitrogen compounds were also added to this treatment in order to maintain a constant ratio of nitrogen atoms to phosphorus atoms. In the other treatment, phosphorus concentrations were left at 0.014 mg/l, the ambient concentration in the lake. Zooplankton and phytoplankton responded differently to these treatments. Zooplankton abundance, biomass, and taxonomic richness decreased with increasing chloride concentration. Zooplankton levels were not affected by the addition of nutrients. The response of phytoplankton to increasing chloride concentration depended on the nutrient concentration present. At the lower nutrient level, the total abundance and biomass of phytoplankton increased with increasing chloride concentration. Phytoplankton taxonomic richness increased up to a chloride concentration of 350 mg/l, and then decreased after that. At high nutrient levels, no relationship was observed between chloride concentration and phytoplankton abundance or biomass, but phytoplankton taxon richness declined with increasing chloride concentration. The combination of high nutrient levels and high chloride concentration resulted in the phytoplankton assemblage being dominated

[644] *E.R. Moffett, H.K. Baker, C.C. Bonadonna, J.B. Shurin, and C.S. Symons, "Cascading Effects of Freshwater Salinization on Plankton Communities in the Sierra Nevada,"* Limnology and Oceanography Letters*, 8:30-37, 2023.*

[645] *K.D. Delaune, D. Nesich, J.M. Goos, and R.A. Relyea, "Impacts of Salinization on Aquatic Communities: Abrupt vs. Gradual Exposures,"* Environmental Pollution, *285:117636, 2021.*

[646] *Greco et al. 2022,* op. cit.

by groups such as cyanobacteria that are difficult for zooplankton to consume.[647] Cyanobacteria lack sterols which are components of zooplankton cell membranes. Dietary deficiencies of these sterols can make zooplankton more sensitive to chloride by increasing the permeability of their cell membranes.[648] Many cyanobacteria species also produce toxins that can limit zooplankton abilities to utilize them as food.[649]

A second mesocosm experiment found that the combination of high salt concentrations and high nutrient concentrations created a very eutrophied system. This included reduced macrophyte coverage of the bottom, higher levels of primary production in the water column, and lowered abundance of consumers at higher trophic levels.[650]

Interactions Between Chloride Salts and the Presence of a Predator

An 83-day mesocosm experiment examined the effects of chloride concentration on an aquatic community in the presence and absence of zooplanktivorous fish.[651] Phytoplankton biomass increased with increasing chloride concentration. The impact was much greater when fish were present. This was due in part to a synergistic effect between the presence of fish and high salt concentrations on zooplankton abundance and biomass. The impacts experienced in these treatments were greater than would be suggested by the effects of either high salinity or fish presence alone.

Are Current Water Quality Standards for Chloride Protective of Ecological Communities?

As noted earlier in this Chapter, Wisconsin's water quality standards include criteria for the protection of aquatic life from chloride. These consist of an acute criterion in which the surface water daily maximum chloride concentration is not to exceed 757 mg/l more than once every three years and a chronic criterion in which the four-day average of daily maximum chloride concentration is not to exceed 395 mg/l more than once every three years. The U.S. Environmental Protection Agency (USEPA) has also issued aquatic life criteria for chloride. These serve as recommendations to states and tribes for setting their water quality criteria. Under the USEPA acute criterion, the one-hour average of chloride concentration should not exceed 860 mg/l more than once every three years. Similarly, under the USEPA chronic criterion, the four-day average chloride concentration should not exceed 230 mg/l more than once every three years.

Both the Wisconsin chloride criteria and the USEPA recommended chloride criteria were developed using data from laboratory toxicity studies for individual species.[652] The effects of chloride and chloride salts on biological communities were not considered in developing these standards. Development and application of these criteria assume that if the criteria are generally protective for the organisms that were tested, they will be protective for biological communities in which these organisms reside. Results from the literature reviewed in this Chapter suggest that this assumption may not be valid.

The studies reviewed in this Chapter document many effects of chloride and chloride salts on organisms and biological communities. These results occur over a wide range of chloride concentrations. A few of the studies present thresholds at which effects appear. These thresholds are summarized in Table 3.17. Impacts for which thresholds have been reported include decreases in organism abundance, reductions in diversity, changes in community composition, changes in organism physiological processes, and changes in organism behavior related to the use of habitats.

[647] *H.W. Paerl and T.G. Otten, "Harmful Cyanobacterial Blooms: Causes, Consequences, and Controls,"* Microbial Ecology, *65:995-1,010, 2013.*

[648] *J. Istant-Navarro, S.E. Arnott, T. Klauschies, and D. Martin-Creuzburg, "Dietary Lipid Quality Mediates Salt Tolerance of a Freshwater Keystone Herbivore,"* Science of the Total Environment*, 769:144657, 2021.*

[649] *J.J. Gilbert, "Susceptibility of Planktonic Rotifers to a Toxic Strain of* Anabaena flos-aquae*,"* Limnology and Oceanography*, 39:1,286-1,297, 1994.*

[650] *Lind et al. 2018,* op. cit.

[651] *Hintz et al. 2017,* op. cit.

[652] *For Wisconsin criteria, see: Chapter NR 105, Surface Water Quality Criteria and Secondary Values for Toxic Substances,* Wisconsin Administrative Code*. For USEPA criteria see: U.S. Environmental Protection Agency,* Ambient Water Quality Criteria for Chloride—1988*," EPA 440/5-88-01, February 1988.*

Table 3.17
Some Chloride Concentration Thresholds for Changes in Biological Communities

Chloride Concentration (mg/l)	Reported Impact	References
5-40	Decreased reproduction and increased mortality in six *Daphnia* Species	Arnott et al., 2020, *Environmental Science and Technology*, 54:9,398-9,407.
16	Reduced bacteria density in biofilms	Cochero et al., 2017, *Science of the Total Environment*, 579:1,496-1,503.
33-108	Reductions in fish diversity	Morgan et al., 2012, *North American Journal of Fisheries Management*, 32:941-952.
35	Substantial changes in composition of periphytic diatom assemblages	Porter-Goff et al., 2013, *Ecological Indicators*, 32:97-106
54	Reductions in wetland plant species richness	Richburg et al., 2001, *Wetlands*, 21:247-255.
100	Decrease in photosynthetic production in common waterweed	Zimmerman-Timm, 2007, In: Lozar, et al., *Water Uses and Human Impacts on the Water Budget*
185	Substantial shift in phytoplankton community composition and reduction in ciliates	Astorg et al., 2023, *Limnology and Oceanography Letters*, 8:38-47.
250	Reductions in zooplankton abundance and diversity	Sinclair and Arnott, 2018, *Freshwater Biology* 63:1,273-1,286.
250-260	Wood frogs and spring peepers stop using ponds for breeding	Sadowski, 2002, *Prairie Perspectives*, 5:144-162; Gallagher et al., 2014, *Wetlands Ecology and Management*, 22:551-564
2,000	Inhibition of denitrification in forested wetlands	Lancaster et al., 2016, *Environmental Pollution*

Source: SEWRPC

Most of the thresholds presented in Table 3.17 are lower than Wisconsin's chronic water quality criterion for chloride and many are lower than the USEPA recommended chronic criterion. This suggests that these water quality criteria may be too high to be fully protective of aquatic communities. It should be noted that these thresholds derive from a small number of studies and may not fully characterize the range of responses aquatic communities might show to chloride enrichment.

A recent study presents stronger evidence that current water quality criteria may not be fully protective of aquatic communities.[653] This study established an experimental network of mesocosm experiments at 16 sites across North America and Europe. Experiments at these sites used standardized methods to examine the effects of chloride on zooplankton and phytoplankton from natural lake habitats. Each experiment incubated zooplankton and phytoplankton from nearby lakes in 20-32 mesocosms at chloride concentrations ranging between 2 mg/l and 1,500 mg/l. These mesocosms were incubated for 41-51 days. The study examined changes in the abundance of zooplankton species from four groups and phytoplankton biomass over the course of the experiment.

At each lake site, the study assessed the concentration of chloride that reduced the abundance of zooplankton in each group by 50 percent. At most sites, this concentration was lower than 230 mg/l, the USEPA chronic criterion (see Table 3.18). The study also assessed the magnitude of reductions seen in each of the zooplankton groups at a chloride concentration of 230 mg/l. While there was considerable variation among sites, for all zooplankton groups reductions greater than 80 percent occurred (see Table 3.18). Food web effects were also observed at some sites, with phytoplankton biomass increasing at 47 percent of the lake sites.

Based on these results, the authors concluded that the current chronic criterion does not protect lake food webs from chloride salt impacts. Based on a similar analysis, they also concluded that the Canadian chronic toxicity standard of 120 mg/l fails to protect lake food webs. The study authors recommended that these criteria be reassessed.

[653] *W.D. Hintz, S.E. Arnott, C.C. Symons, D.A. Greco, A.McClymont, J.A. Brentrup, M. Canedo-Arguelles, A.M. Derry, A.L. Downing, D.K. Gray, S.J. Melles, R.A. Relyea, J.A. Rusak, C.L. Searle, L. Astorg, H.K. Baker, B.E. Beisner, K.L. Cottingham, Z. Ersoy, C. Espinosa, J. Franceschini, A.T. Giorgio, N. Gobeler, E. Hassal, M.-P. Hebert, M. Huynh, S. Hylander, K.L. Jonasen, A.E. Kirkwood, S. Langenheder, O. Langvall, H. Laudon, L. Lind, M. Lundgren, L. Proia, M.S. Schuler, J.B. Shurin, C.F. Steiner, M. Striebel , S. Thibodeau P Urrutia-Cordero, L. Vendrell-Puigmitja, and G.A. Weyhenmeyer, "Current Water Quality Guidelines Across North America and Europe Do Not Protect Lakes from Salinization," Proceedings of the National Academy of Sciences, 119:e2115033119, 2022.*

Table 3.18
Reductions in Zooplankton Abundance Relative to the USEPA Recommended Criterion Continuous Maximum Concentration

Zooplankton Group	Percent of Sites Showing 50 Percent Reductions at Chloride Concentrations Below 230 mg/l	Range of Reductions Observed at a Chloride Concentration of 230 mg/l (percent)
Cladocera	86	22-83
Calanoid copepods	90	15-96
Cyclopoid copepods	60	13-96
Rotifers	82	10-100

Source: W.D. Hintz et al., "Current Water Quality Guidelines Across North America Do Not Protect Lakes from Salinization," Proceedings of the National Academy of Sciences,*" 119:e2115033119, 2022*

3.4 IMPACTS OF CHLORIDE ON ECOSYSTEMS

Ecosystem Functions and Structures

An ecosystem consists of the organisms within an area and the physical environment with which those organisms interact. A stream ecosystem, for example, includes the plants, animals, and microorganisms in the stream as well as the water of the stream, the sediment and rock making up the streambed, and the soil making up the stream bank. Ecosystems may be linked to one another through movement or exchange of matter or energy.

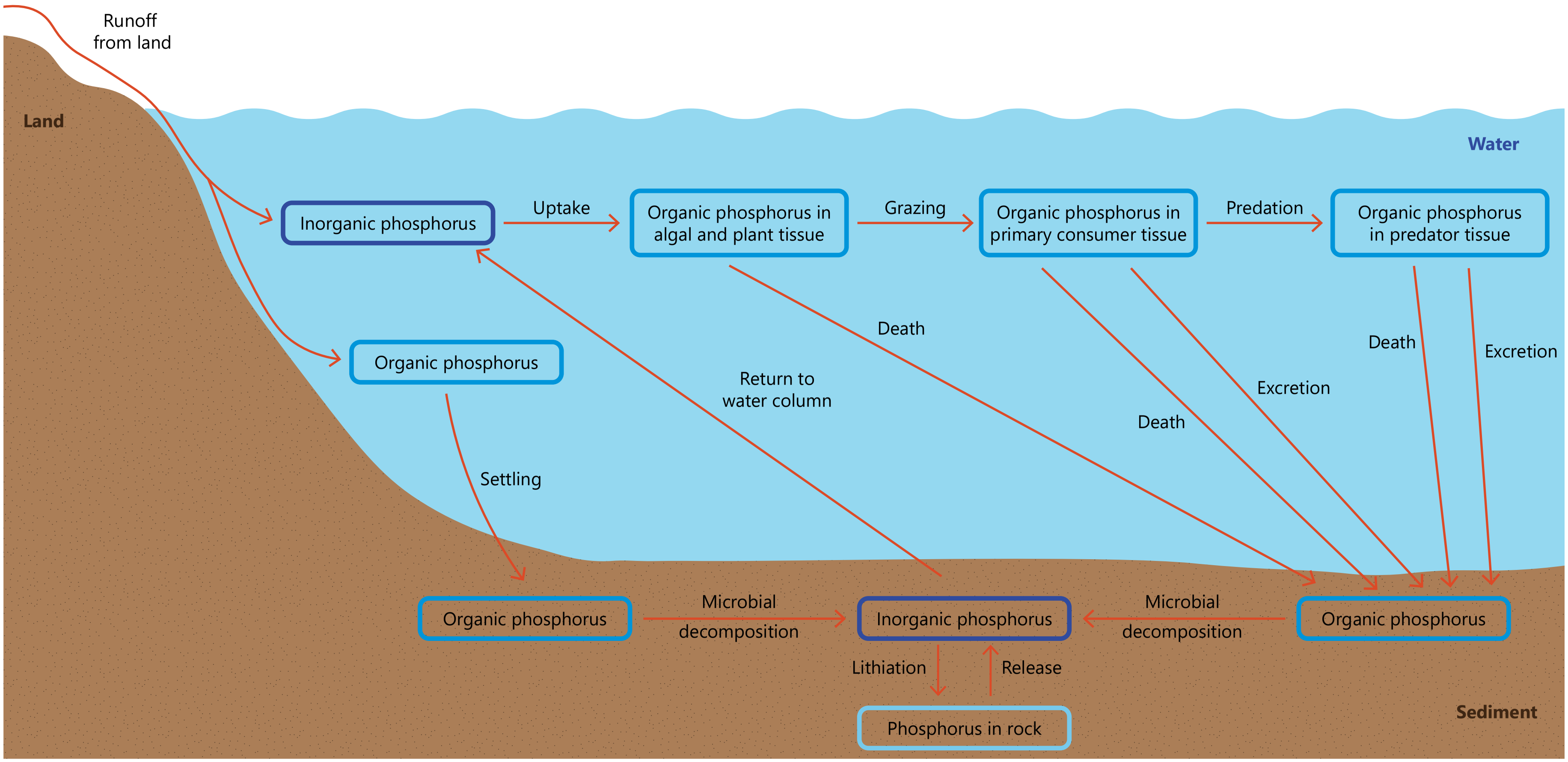
Ecosystems provide numerous services to humans. These include the provision of fresh water through the hydrologic cycle, development and maintenance of soils, decomposition of wastes, regulation of the climate, and food.

An ecosystem is described through the movement and transformation of materials and energy through various compartments in the environment. Figure 3.18 shows a simplified depiction of phosphorus movement through a pond ecosystem. Organic phosphorus compounds from the land surface are carried into the pond as detritus in runoff. This detritus settles onto the pond bed and is incorporated into sediment. Runoff also carries inorganic phosphorus compounds into the pond. Algae and plants in the pond take up inorganic phosphorus and incorporate it into their tissue. Herbivorous animals consume algae and plants and incorporate the phosphorus contained in this food into their own tissue. Similar incorporation of phosphorus into predator tissue occurs when other animals consume the herbivores. When organisms die, their bodies sink to the pond bed and are incorporated into sediment. Excretory products from animals also sink and are incorporated into sediment. Bacteria within the sediment decompose this organic material, converting organic phosphorus compounds to inorganic phosphorus compounds. Inorganic phosphorus in the sediment can be released back into the water column. Over time, some inorganic phosphorus in sediment may be incorporated into rock as sediments lithify. Similarly, degradation of rock may release phosphorus to the sediment or water.

The flow of material through ecosystems is often cyclic. This is often examined as cycles of chemical elements. An example of this is the nitrogen cycle which was described in Chapter 2 of this Report (see Figure 2.17). Cycling of material can involve changes in the location of the element in the environment. For example, a change in solubility may result in an element moving from sediment into the water column. These changes may involve movement between biotic and abiotic compartments of the environment. The chemical form of an element may also change through biogeochemical transformations that occur during cycling. Some of these transformations occur through purely chemical mechanisms. For example, when a carbon dioxide (CO_2) molecule dissolves in water it combines with a water molecule to form carbonic acid (H_2CO_3) which then dissociates to form a bicarbonate ion (HCO_3^-). Other transformations are biologically mediated. Nitrogen fixation, nitrification, and denitrification, which were discussed in Chapter 2 of this Report, are examples of biologically mediated transformations. Each of these steps in the nitrogen cycle is conducted by a specific species of bacteria.

Cycling of nutrients through food webs is an example of an ecosystem process. Other examples of processes include primary production through photosynthesis or chemosynthesis, community respiration, and decomposition of organic matter. Increasing concentrations of chloride salts and salinity may have impacts on these processes in terrestrial and freshwater ecosystems. This may in turn affect the ability of these ecosystems to provide ecosystem services.

Figure 3.18
Ecosystem Movement of Phosphorus Through a Pond Ecosystem



Source: SEWRPC

Chloride salts and salinity can have impacts on ecosystem processes. Impacts of chloride on several nutrient cycles were previously discussed in the section on impacts on wetlands in Chapter 2 of this Report. This section describes the impacts of chloride salts and salinity on energy flow.

Energy Flow Through Ecosystems

Energy flows through ecosystems. Organic carbon compounds represent the basic energy for ecosystems. While these compounds are all ultimately formed through primary production, mostly via photosynthesis, they are provided within ecosystems both through primary production and organic matter decomposition.[654]

The relative importance of the processes of primary production and decomposition to energy flow varies depending on the specific ecological system. In streams the relative importance of these processes as energy sources depends on the size or order of the stream. In general, photosynthesis becomes relatively more important in higher order, downstream sections of the stream network.[655] For example, a study of the Little Tennessee River in Georgia and North Carolina assigned about 81 percent of available organic carbon of the entire stream network to gross primary production.[656] Most of this organic carbon was in the lower reaches.

The size of a lake partially determines the relative importance of primary production and decomposition as energy sources. Most lakes are relatively small, and the littoral area can represent a large portion of their surface area. Breakdown of terrestrial organic material originating in the watershed can represent a large portion of the energy process in the lake. Photosynthesis may be more important in larger lakes; however, much of the organic material produced through primary production in these lakes will ultimately end up being decomposed.

The relative importance of primary production and decomposition as energy sources is dynamic. As indicated in the Little Tennessee River example, it can vary by location within an ecosystem. It can also vary seasonally with climatic changes or loading of organic material from upstream or terrestrial sources.

Freshwater aquatic food webs are dependent on inputs of organic material from surrounding terrestrial landscapes for energy and nutrients.[657] While some of this material enters aquatic systems as dissolved organic matter, much enters as detritus such as leaves, wood, dead organisms, and other forms of particulate organic material. Leaf litter in particular is a major organic carbon source that sustains biomass at higher trophic levels in temperate forest and low order streams.[658] Microbial organisms such as bacteria and fungi colonize this litter, decomposing it. These microbes may either assimilate carbon from the litter to create more biomass or respire it. The underlying mechanisms determining the balance between these two physiological processes is not well understood. Colonization of the litter by microbes also mineralizes nutrients from the litter, making them available to support primary production and the growth of primary producers.[659]

Microbial conditioned litter is a major energy source for many aquatic organisms. While many macroinvertebrates feed on leaf litter, they are unable to digest the leaves. The bacteria, fungi, and periphyton growing on the litter provide them with energy and nutrients. This allows the energy in the litter to enter the aquatic food web and be passed to higher trophic levels. By processing microbially conditioned litter,

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[654] *R.B. Schäfer, M. Bondschuh, D.A. Rouch, E. Szöcs, P.C. van der Ohe, V. Pettigrove, R.Schulz, D. Negrgoda, and B.J. Kefford, "Effects of Pesticide Toxicity, Salinity, and Other Environmental Variables on Selected Ecosystem Functions and the Relevance for Ecosystem Services,"* Science of the Total Environment*, 415:69-78, 2012.*

[655] *R. L. Vannote, W.G. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing, "The River Continuum Concept,"* Canadian Journal of Fisheries and Aquatic Sciences*, 37:130-137, 1980.*

[656] *J.R. Webster, "Spiraling Down the River Continuum: Stream Ecology and the U-Shaped Curve,"* Journal of the North American Benthological Society*, 26:375-389, 2007.*

[657] *A.B. Stoler, W.D. Hintz, D.K. Jones, L. Lind, B.M. Mattes, M.S. Schuler, and R.A. Relyea, "Leaf Litter Mediates the Negative Effect of Road Salt on Forested Wetland Communities,"* Freshwater Science*, 36:415-426, 2017.*

[658] *E. Berger, O. Frör, and R.B. Schäfer, "Salinity Impacts on River Ecosystem Processes: A Mini-Review,"* Philosophical Transactions of the Royal Society Series B*, 374:20180010, 2018.*

[659] *M.J. Rubbo, J.J. Cole, and J.M. Kiesecker, "Terrestrial Subsidies of Organic Carbon Support Net Ecosystem Production in Temporary Forest Ponds: Evidence from an Ecosystem Experiment,"* Ecosystems*, 9:1,170-1,176, 2006.*

macroinvertebrates provide a link between terrestrial flora and aquatic food webs.[660] In fact, the amount and type of terrestrial plant litter available may limit energy flow in some aquatic ecosystems.[661]

There can be a spatial dimension to energy flow in some systems. Water flow in stream systems can transport material including both dissolved and particulate organic matter downstream. As a result, primary production and decomposition in a stream provide energy to both local food webs and food webs downstream.[662]

Toxicity and other effects of chloride salts and salinity on organisms could potentially disrupt linkages between trophic levels in some environments. These linkages constitute pathways for energy flow in environments. These sorts of impacts on energy flow are likely to vary among systems depending on how much redundancy in functional roles there is among the species present.[663] If each role is performed by multiple species and if species performing a given role differ in their sensitivity to chloride salts, the effects of chloride might have little impact on energy flow. Impacts on energy flow are more likely to occur when either a small number of species perform a critical role or when species performing similar roles have similar sensitivity to chloride.

Impacts of Chloride Salts and Salinity on Organic Matter Decomposition

In general, organic matter decomposition in streams decreases with increasing salinity.[664] For example, one field study found that the breakdown rate of leaf packs placed in streams decreased with increasing salinity over a range of specific conductance between 50 and 3,500 μS/cm.[665] The biomass of fungi on and in the leaves also decreased with rising salinity. The same study reported similar results for the breakdown of cotton strips that were placed in a stream. A second field study reported that the breakdown rates of birch wood sticks placed in streams decreased with increasing salinity.[666] This study found that fungal biomass and microbial activity both were reduced with increasing salinity.

Similar results have been reported from mesocosm studies. One mesocosm study found that the mass loss of decomposing leaves decreased with increasing salinity.[667] In this study, fungal biomass in the leaves rose with increasing salinity at low levels of salinity, and then decreased with increasing salinity at higher levels of salinity. A second mesocosm study, which also found decreasing mass loss from decomposing leaves with increasing salinity, found that fungal respiration, an indicator for fungal activity, fell with increasing salinity.[668] A third study did not detect any effect of salinity on litter breakdown rates.[669]

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[660] *M.A. Palmer, A.P. Covich, S. Lake, P. Biro, J.J. Brooks, J. Cole, C. Dahm, J. Gibert, W. Goedkoop, K. Martens, J. Verhoeven, and W.J. van de Bund, "Linkages Between Aquatic Sediment Biota and Life Above Sediments as Potential Drivers of Biodiversity and Ecological Processes,"* BioScience, *50:1,062-1,075, 2000.*

[661] *J.B. Wallacd, S.L. Eggert, J.L. Meyer, and J.R Webster, "Effects of Resource Limitation on a Detrital-Based Ecosystem,"* Ecological Monographs, *69:409-433, 1999.*

[662] *J.D. Allan and M.M. Castillo,* Stream Ecology: Structure and Function of Running Waters, *Springer-Verlag, Dordrecht, Netherlands, 2007.*

[663] *D. Tilman, J. Knops, D. Wedin, and P. Reich, "Experimental and Observational Studies of Diversity, Productivity, and Stability," pages 42-70 in: A.P Kinzig, S.W. Pacala, and D. Tilman,* The Functional Consequences of Biodiversity: Empirical Progress and Theoretical Extensions, *Princeton University Press, Princeton, New Jersey, 2002.*

[664] *Berger et al 2018,* op. cit.

[665] *Schäfer et al 2012,* op. cit.

[666] *R. Gómez, A.D. Asencio, J.M. Picón, R. del Campo, M.I. Arce, M. del Mar Sánchez-Montoya, M.W. Suárez, and M.R. Vidal-Abarca, "The Effect of Water Salinity on Wood Breakdown in Semiarid Mediterranean Streams,"* Science of the Total Environment, *541:491-501, 2016.*

[667] *M. Cañedo-Argüelles, M. Bundschuh, C. Gutiérrez-Cánovas, B.J. Kefford, N. Prat, R. Trobajo, and R.B Schäfer, "Effects of Repeated Salt Pulses on Ecosystem Structure and Functions in a Stream Mesocosm,"* Science of the Total Environment, *476-477:634-642, 2014.*

[668] *C. Canhoto, S. Simões, A.C. Gonçalves, L. Guihermino, and F. Bärlocher, "Stream Salinization and Fungal-Mediated Leaf Decomposition: A Microcosm Study,"* Science of the Total Environment, *599-600:1,638-1,645, 2017.*

[669] *Stoler et al 2017,* op. cit.

Some studies have tied reductions in organic material decomposition rates to chloride concentrations. A 16-day study found that a chloride concentration of 5,000 mg/l reduced the decomposition of beech tree litter incubated in laboratory chambers by 44 percent.[670] A 75-day study found that a chloride concentration of 645 mg/l reduced the breakdown rate of oak leaf litter in pond mesocosms at by almost 10 percent.[671]

The mechanisms through which chloride salts reduce the rates of decomposition of organic matter are not well understood. It is likely that toxicity effects on fungi and bacteria play a role. It has been suggested that elevated concentrations of chloride salts may impair the activities of enzymes that microbial decomposers use to process litter.[672] Another suggestion is that elevated salt levels may reduce the functional capacities of decomposers.[673] Effects of salinity on macroinvertebrates may also play a role, as the physical breakdown of litter by macroinvertebrates can be important in the colonization of leaf litter by microbes.[674]

Reductions in the breakdown of organic matter could lead to less biomass in an aquatic ecosystem. This depends on whether the primary production through photosynthesis within the system is sufficient to maintain overall levels of production.[675] In watersheds with sparser riparian vegetation, instream or in-lake autotrophic organisms such as phytoplankton and aquatic plants are the most important sources of organic carbon. If these sources can sustain biomass decomposition in the presence of elevated concentrations of chloride salts, reduced decomposition of litter will have little effect on production at higher trophic levels. Where autotrophic sources cannot sustain biomass, reduced decomposition due to elevated chloride salt concentrations could have several effects. The amount of biomass at higher trophic levels might be reduced. If the magnitude of the reduction in biomass due to reduced decomposition is great enough, this could include a reduction in the number of trophic levels the system could support. Reduced decomposition due to increased concentrations of chloride salt could also result in an accumulation of litter on the bed and in the sediment of the stream or lake. Over time, this would lead to changes in habitat. Finally, in streams the reduced decomposition of litter could result in transport of organic material downstream. This could have indirect impacts affecting production in downstream reaches through reducing light penetration, altering energy flow from upstream, or changing habitat conditions. It should be noted that this first impact could potentially lead to reductions in primary production in downstream reaches while the other two impacts might affect production at higher trophic levels.

Impacts of chloride salts and salinity on the decomposition of organic matter may also affect biogeochemical transformations of other elements, potentially disrupting other biogeochemical cycles. Biogeochemical cycles of biologically active elements are linked, especially through physical and chemical changes that occur in sediment.[676] Many biotransformations of other elements are dependent on the availability of organic carbon to provide the energy source for the bacteria that mediate the transformations.[677] Examples of these include the nitrification and denitrification reactions discussed in Chapter 2 of this Report.

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[670] *C.M. Swan and C.A. DePalma, "Elevated Chloride and Consumer Presence Independently Influence Processing of Stream Detritus,"* Urban Ecosystems*, 15:625-635, 2012.*

[671] *R.J. Van Meter, C.M. Swan, and C.A. Trossen, "Effects of Road Deicer (NaCl) and Amphibian Grazers on Detritus Processing in Pond Mesocosms,"* Environmental Toxicology and Chemistry*, 31:2,306-2,310, 2012.*

[672] *M.C. Roache, P.C. Bailey, and P.I. Boon, "Effects of Salinity on the Decay of the Freshwater Macrophyte,* Triglochin procerum," Aquatic Botany*, 84:45-52, 2006.*

[673] *Van Meter et al 2012,* op. cit.

[674] *M. Santonja, L. Pellan, and C. Piscart, "Macroinvertebrate Identity Mediates the Effects of Litter Quality and Microbial Conditioning on Leaf Litter Recycling in Temperate Streams,"* Ecology and Evolution*, 8:2,542-2,553, 2018.*

[675] *K.M. Fritz, S. Fulton, B.R. Johnson, C.D. Barton, J.D. Jack, D.A. Word, and R.A. Burke, "Structural and Functional Characteristics of Natural and Constructed Channels Draining a Reclaimed Mountaintop Removal and Valley Fill Coal Mine,"* Journal of the North American Benthological Society*, 29:673-689, 2010.*

[676] *J.J. Middelburg and L.A. Levin, "Coastal Hypoxia and Sediment Biogeochemistry,"* Biogeosciences*, 6:1,273-1,293, 2009.*

[677] *T.A. Newcomer, S.S. Kaushal, P.M. Mayer, A.R. Shields, E.A. Canuel, P.M. Groffman, and A.J. Gold, "Influence of Natural & Novel Organic Carbon Sources on Denitrification in Forested, Degraded-Urban, and Restored Streams,"* Ecological Monographs*, 82:449-466, 2012; S-.W. Dawn, and S.S. Kaushal, "Warming Increased Carbon and Nutrient Fluxes from Sediments in Streams Across Land Use,"* Biogeosciences*, 10:1,193-1,207, 2013.*

Impacts of Chloride Salts and Salinity on Primary Production

The impact of increased concentrations of chloride salts and salinity on primary production is uncertain. Results from some studies suggest that salinity increases may reduce primary production in freshwater aquatic systems, while results from other studies suggest that this may not be the case. Several studies found that vascular plant communities show reduced primary production in response to increasing salinity.[678] A different study found that primary production in diatoms assemblages increased with increasing salinity.[679] Still other studies suggest that at low salinities primary production may rise with increasing salinity, while at higher salinity primary production may decrease with increasing salinity.[680]

Some results from studies examining the effects of chloride salts and salinity on freshwater organisms suggest that increases in the concentrations of chloride could result in reductions in primary production in aquatic systems. As discussed in the section on effects on algae in this Chapter, some studies have reported that increases in concentrations of chloride salts can lead to reductions in algal concentrations in the water column, reduced photosynthetic pigment content in algal cells, and reduced algal photosynthetic efficiency. Some similar effects have been reported for some other photosynthesizing organisms. As discussed in the section on the effects on aquatic organisms in this Chapter, higher chloride salt concentrations have been reported to induce growth reductions, reductions in biomass, and reduced carbon fixation in aquatic macrophytes.

Finally, the ability of water to hold gases in solution decreases with increasing salinity.[681] Increases in chloride salt concentration could reduce the amount of carbon dioxide available to aquatic plants and algae for photosynthesis.

Impacts of Chloride Salts and Salinity on Ecosystem Services

Increased concentrations of chloride salts and salinity could potentially affect the ability of some systems to provide ecosystem services. Ecosystem processes such as organic matter breakdown and primary production provide the basis for many potential ecosystem services.[682] This section discusses a few examples in which reductions in energy flow could potentially lead to impacts on ecosystem services.

A reduction in the decomposition of organic matter due to higher concentrations of chloride salts could lead to less biomass in a stream or lake system.[683] Given that fish generally occupy higher trophic levels in these systems, such a reduction could potentially reduce the sizes and quality of fish populations in a waterbody. This could reduce the ability of the waterbody to provide food to humans. It could also reduce the recreational opportunities provided by a healthy and diverse fish assemblage.

As previously discussed, decomposition of organic material provides the energy for many biogeochemical transformations. These transformations are important in cycling of elements, such as in the nitrogen cycle. Reductions in organic matter breakdown due to higher concentrations of chloride salts could lower the amount of material processed in nitrogen cycle steps such as denitrification. This could cause increases in the ambient concentrations of nitrogen compounds in aquatic ecosystems because the ability of the system to convert nitrate into nitrogen gas would be reduced under such conditions. This change would represent a reduction in the ability of the ecosystem to provide water purification services.

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[678] *See, for example, W.E. Odum, "Comparative Ecology of Tidal Freshwater and Salt Marshes,"* Annual Review of Ecology and Systematics*, 19:147-176, 1988; D.L. Nielsen, M.A. Brock, N. Rees, and D.S. Baldwin, "Effects of Increasing Salinity on Freshwater Ecosystems in Australia,"* Australian Journal of Botany*, 51:655-665, 2003.*

[679] *M.G. Ros, J.P. Marín-Murcia, and M. Aboal, "Biodiversity of Diatom Assemblages in a Mediterranean Semiarid Stream: Implications for Conservation,"* Marine and Freshwater Research*, 60:14-24, 2009.*

[680] *Silva and Davies 1999,* op. cit.*; E.I.L. Silva, A. Shimizu, and H. Matsunami, "Salt Pollution in a Japanese Stream and Its Effects on Water Chemistry and Epilithic Algal Chlorophyll-a,"* Hydrobiologia*, 437:139-148, 2000.*

[681] *R.F. Weiss, "Carbon Dioxide in Water and Seawater: The Solubility of a Non-Ideal Gas,"* Marine Chemistry*, 2:203-215, 1974.*

[682] *Berger et al 2018,* op. cit.

[683] *Fritz et al 2010,* op. cit.

A study of two rivers in Poland found that increases in salinity reduced the ability of these ecosystems to provide another water purification service. While the use of sulfonamide antibiotics to treat human diseases has decreased in recent decades, these drugs are commonly used in veterinary applications. The study found that degradation rates of four sulfonamides in river water decreased with increasing salinity.[684]

3.5 SUMMARY

Review of the scientific and technical literature indicates that increased concentrations of chloride salts can cause adverse impacts on biological systems. These impacts can occur at several biological levels affecting individual organisms, species, communities and ecosystems. While limited research has been conducted on some groups of organisms, the available studies suggest that chloride salts can produce several different types of impacts.

- Many biological impacts are caused by toxicity of chloride, the cations associated with chloride, or salinity to aquatic organisms
    - Organisms differ from one another in their sensitivity to toxic effects from chloride salts
    - The toxicity of chloride salts can be influenced by many factors including:
        - The level, frequency, duration, and manner of exposure
        - Environmental factors such as temperature and water hardness
        - The biology and developmental stage of the organism
    - Chloride salt toxicity can occur through acute or chronic exposure
    - Chloride salts can produce lethal and sublethal effects
- While different impacts have been reported in different organisms, numerous types of sublethal effects are associated with exposure to chloride salts including:
    - Lower population growth rates
    - Reduced organismal growth and slower development
    - Smaller organism size
    - Physical and cellular damage
    - Reduced activity including less feeding, mobility, and antipredator and antiparasite behavior
    - Less abundance
    - Reduced longevity
    - Reductions in photosynthesis due to reduced leaf production, reduced photosynthetic pigment content, and physiological effects
    - Interference with reproduction through several mechanisms
    - Reduced assimilation of food and nutrients

[684] *E. Adamek, W. Baran, and A. Sobczak, "Assessment of the Biodegradability of Selected Sulfa Drugs in Two Polluted Rivers in Poland: Effects of Seasonal Variation, Accidental Contamination, Turbidity, and Salinity,"* Journal of Hazardous Materials, *313:147-158, 2016.*

    - Induction of developmental deformities
    - Increased energy requirements
    - Behavioral alterations
- Some factors may act to mitigate an organism's sensitivity to impacts of chloride salts including greater food availability, higher water hardness, and specific biological traits
- Increases in concentration of chloride salts can cause changes in composition and structure of ecological communities including:
    - Changes in which species are present
    - Reductions in taxonomic richness, evenness, and diversity
    - Reductions in abundance and biomass of organisms
- Increased concentrations of chloride salts may alter outcomes of ecological processes such as competition and predation
- Changes in community composition and structure may occur at chloride concentrations lower than the Wisconsin chronic chloride criterion of 395 mg/l, suggesting that current water quality standards may not be protective of ecological communities
- Increases in the concentrations of chloride salts in the environment have impacts to the energy flow through an ecosystem due to
    - Decreases in primary production
    - Decreases in organic matter breakdown
- Chloride induced changes in energy flow could reduce the ability of some ecosystems to provide certain services to humans (e.g., recreational fishing)

IMPACTS OF CHLORIDES ON INFRASTRUCTURE AND THE BUILT ENVIRONMENT 4

Credit: Wikimedia Commons User Tim Green

4.1 INTRODUCTION

Chloride salts have wide commercial and industrial uses that result in chloride contamination of the natural and built environment. Major uses contributing chloride to the environment include snow and ice control operations, water softening, water treatment processes, agricultural practices, food processing, and chemical manufacturing. In snow and ice control operations, sodium chloride (NaCl),[685] magnesium chloride ($MgCl_2$), and calcium chloride ($CaCl_2$) are used for deicing roads, sidewalks, parking lots, and driveways. Dissolved chloride salts reduce the freezing temperature of water, which reduces the amount of ice formation. In water softening, NaCl and potassium chloride (KCl) are used to reduce the hardness of water. The salts participate in an ion-exchange process in which calcium and magnesium ions in the water, which contribute to hardness, are replaced with sodium or potassium ions from the salt. In drinking water and wastewater treatment, aluminum chloride ($AlCl_3$) and ferric chloride ($FeCl_3$) are used as coagulants to remove contaminants. In agriculture, potash (KCl) is used in fertilizers to deliver potassium as a nutrient to crops. In food processing, NaCl is used in a wide range of applications such as preserving food, seasoning, coloring, maintaining food texture, and regulating fermentation and chemical reactions. Lastly, various chloride salts are used in many chemical manufacturing processes. In general, NaCl is the most widely used chloride salt across industries due to its lower cost and availability. The disadvantage of using chloride salts in the built environment is that they can induce and accelerate damage to various types of infrastructure and reduce their useful life.

This chapter evaluates mechanisms and impacts of corrosion in metals such as metallic bridges, reinforcing steel in concrete, roadside infrastructure, water supply infrastructure, vehicle metal components, and mechanisms and impacts of deterioration in concrete such as roads, bridges, and buildings. This chapter also briefly discusses impacts to other infrastructure such as power systems and railroads.

4.2 CHORIDE-INDUCED METAL CORROSION MECHANISMS

Corrosion is a natural electrochemical process in which the refined metal is oxidized and is converted into more chemically stable metallic oxide compounds. All metals are subject to similar corrosion mechanisms. Figure 4.1 shows photos of typical corrosion occurring on a bridge, a culvert, and a motor vehicle. In the

[685] *Acronyms and abbreviations used in this report are defined in Appendix A.*

case of iron and its alloy steel, ferric oxide is formed when the iron is corroded. Corrosion develops when electrochemical reactions occur between the metal, water, and oxygen. Corrosion occurs by means of the flow of electrons in a process similar to what happens in a battery. When water contacts metal, the metal surface provides microscopic sites that act as anodes and cathodes. Electrons flow through the metal between the anodic and cathodic sites.

Figure 4.2 illustrates a typical iron corrosion process. On the figure, metallic iron at the anode is oxidized in the presence of water into iron(II) in the following reaction and is dissolved into solution as ions:

$$Fe \rightarrow Fe^{2+} + 2e^{-}$$

The cathode, often at locations of impurities in the metal, receives the electrons from the iron oxidation. The electrons then reduce oxygen at the cathode. Under acidic conditions, the electrons, oxygen, and hydrogen ions in the water react to produce additional water molecules in the following reaction:

$$O_2 + 4H^{+} + 4e^{-} \rightarrow 2H_2O$$

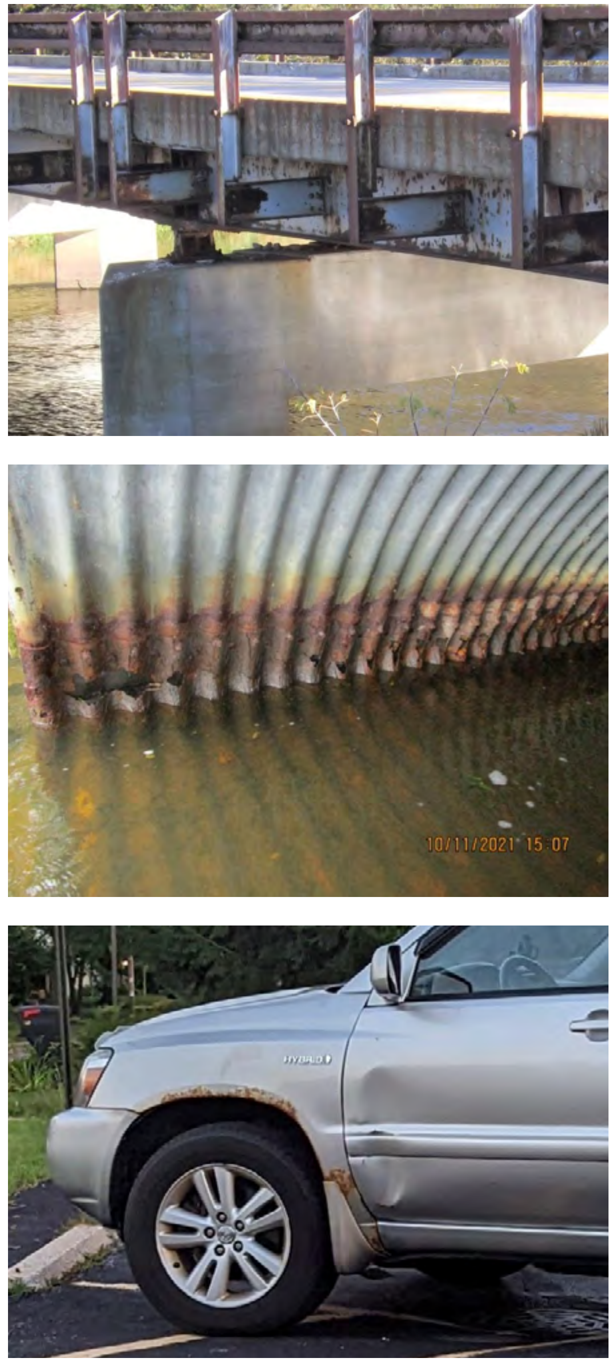
Under neutral or alkaline conditions, the electrons, oxygen, and water react to form hydroxide ions in the following reaction:

$$O_2 + H_2O + 4e^{-} \rightarrow 4OH^{-}$$

Iron(II) ions from the anode further react with hydroxide ions in the water and are oxidized by oxygen to form iron oxides known as rust. Several chemical reactions can be involved, and different types of rust can result depending on the availability of oxygen and water. Most common types of rust include hydrated ferric oxides ($Fe_2O_3 \cdot nH_2O$) and ferric oxide-hydroxide ($Fe(OH)_3$). In low moisture environments, ferric oxide (Fe_2O_3) may result. In rare cases of a prolonged low oxygen environment, iron(II) may be favored, resulting in magnetite (Fe_3O_4) or ferrous oxide (FeO).

The addition of chloride anions, such as from road salt, greatly increases the rate of metallic corrosion. The primary factor for the higher rate of corrosion is the increased conductivity of the solution. Chloride is a strong electrolyte. The presence of electrolytes in water increases the speed of electron transfer between anode and the cathode. This increases the rate of corrosion.[686] Chloride salts also decrease the freezing point of water which may increase the contact time between the liquid water and the metal surface. This allows the corrosion process to occur over a longer period and a wider range of temperatures.

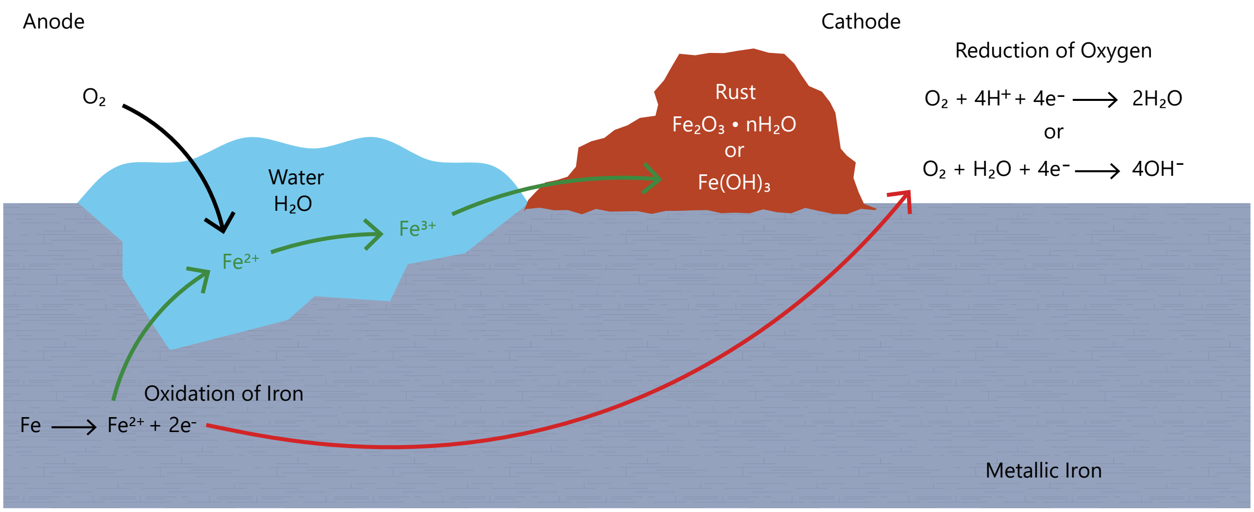
Figure 4.1
Metallic Corrosion on a Bridge, Culvert, and Motor Vehicle



Source: WisDOT and SEWRPC

[686] *Levelton Consultants Limited, "Guidelines for the Selection of Snow and Ice Control Materials to Mitigate Environmental Impacts," National Cooperative Highway Research Program Report 577, 2007.*

Figure 4.2
Typical Iron Corrosion Process



Source: SEWRPC

A wide variety of metals are used in road infrastructure, bridges, and motor vehicles. The most common metals are iron, steel, aluminum alloys, magnesium alloys, copper, and copper alloys. Cast iron is used in motor vehicle engines and drive train components, roadside infrastructure, and bridges. Steel, which includes a wide range of alloy compositions and manufacturing methods, is typically used in concrete reinforcement, steel bridges, and motor vehicle structural components, body panels, fuel tanks, fittings, and tubing. $CaCl_2$ is more corrosive to steel than either NaCl and $MgCl_2$.[687] Aluminum alloys are also used both in motor vehicle components and roadside infrastructure such as guardrails, handrails, and light poles. Magnesium alloys are used for motor vehicle wheels, transmission housings, and various brackets and supports. Copper and cooper alloys are used primarily for electrical wiring and electrical contacts in motor vehicles, roadside infrastructure, and bridges. These diverse metals have different susceptibility to corrosion. In general, iron, steel, and magnesium alloys are highly susceptible to corrosion, while aluminum and copper alloys are less susceptible. When aluminum and copper corrode in air, a protective oxide layer is formed on the surface of the metal. The oxide layer prevents oxygen from contacting the metal atoms underneath and protects the metal from further corrosion.[688]

Corrosion Inhibitors

Due to the corrosive impacts of chloride-based deicers to metal infrastructure, reinforced concrete, and motor vehicles, corrosion inhibitors are often added to deicers. Corrosion inhibitors are chemical substances added in small amounts that reduce or prevent the deterioration of metals in corrosive environments. According to a 2014 Idaho Transportation Department research report, the Wisconsin Department of Transportation (WisDOT) uses corrosion inhibitors in 10 to 50 percent of dry salt and salt brine applications.[689]

Several types of corrosion inhibitors exist. Some inhibit the electrochemical reactions that occur at the anode or cathode sites on the metal. Others form a physical barrier on metal surfaces that inhibits corrosion. Anodic inhibitors include phosphates, carbonates, and silicates. These are highly effective at preventing corrosion of iron-based alloys in laboratory testing. However, when they are present at low concentrations such as when they become diluted, anodic inhibitors may increase rather than inhibit corrosion in localized areas. Cathodic inhibitors include calcium bicarbonate, zinc ions, polyphosphates, and phosphonates. They are generally less effective than anodic inhibitors; however, they are considered safer than anodic inhibitors

[687] *Massachusetts Department of Transportation, "MassDOT Snow and Ice Control Program 2017 Environmental Status and Planning Report," EEA# 11202, 2017.*

[688] *Levelton Consultants Limited, 2007,* op. cit.

[689] *P.C. Casey, C.W. Alwan, C.F. Kline, G.K. Landgraf, and K.R. Linsenmayer, "Impacts of Using Salt and Salt Brine for Roadway Deicing," Idaho Transportation Department Research Report, 2014.*

because they can decrease general corrosion without increasing localized corrosion attacks.[690] Inhibitors that form a physical barrier include organic compounds derived from agricultural biproducts, such as juice from sugar beets. In general, they protect metals by physical adsorption, chemisorption, and film formation on the metal surface.[691]

The formulations of most commercially available inhibitors are proprietary and are generally derived from agricultural byproducts. This makes them difficult to classify or study. It is worth noting that while these commercial inhibitors in deicers reduce corrosion of metal infrastructure, they can have other impacts on the environment. For example, the beet juice used in many commercial inhibitors can increase biochemical oxygen demand and deplete oxygen levels in waterways. Similarly, the phosphorous compounds used in many commercial inhibitors may contribute to eutrophication of surface waterbodies. The sensitivity of receiving waters to these compounds can vary widely. The quantity, type, and application locations of corrosion inhibitors should be adapted based on local conditions. For example, the application of corrosion inhibitors can be reduced or eliminated near waterbodies with algal bloom issues.

4.3 DEICER-INDUCED CONCRETE DETERIORATION MECHANISMS

Concrete structures including roads, buildings, and bridges are susceptible to deterioration caused by deicers. Portland cement concrete is a hardened composite material made from stone and sand aggregates bonded together by hydrated cement paste. In most infrastructure applications concrete is reinforced with steel reinforcement bars (rebar). Examples of infrastructure built with steel-reinforced concrete include bridge decks and abutments, road expansion joints, and building support structures. Based on current research, three primary concrete deterioration mechanisms have been identified which include physical damage caused by salt scaling, chemical reactions between deicers and cement binders, and alkali-aggregate reactions increased by deicers.

Salt Scaling Effect

During winter conditions, freeze-thaw cycles for water in the concrete cement pores produce expansive forces that cause scaling on the concrete surface. This scaling removes the cement paste on the surface layer and successively removes lower cement paste layers. As cement is removed, concrete aggregates and sand are exposed to the environment, encouraging further damage to the concrete. Figure 4.3 shows concrete scaling damage. The rate at which scaling occurs and the magnitude of scaling damage are significantly increased in the presence of deicers. The precise mechanism of salt scaling damage is not well understood. Several mechanisms have been proposed including the following:[692]

Figure 4.3
Concrete Scaling Damage

Source: SEWRPC

- Salt applications increase the frequency of freeze-thaw cycles that cause progressive expansion of the cement paste due to hydraulic pressure in the cement pores.

- Salt concentration gradients in the concrete cause water movement in the cement pores that creates osmotic pressure in the concrete during freezing conditions.

[690] *Levelton Consultants Limited, 2007,* op. cit.

[691] Ibid.

[692] *J. Cao,* A Study of Effects of a New Agricultural-Based Deicer on the Properties of Pavement Concrete*, Master's Thesis, Iowa State University, Ames, Iowa, 2014.*

- Salt in the cement pore solutions create differences in vapor pressure between liquid water and ice that cause water movement in the concrete.
- Crystallization of salt can occur as saline water in the concrete freezes.
- Glue spall may occur (see Figure 4.4). Ice contracts and expands with temperature change more than concrete. When water freezes over a concrete surface, its contraction and expansion create tensile stress on the concrete surface. When the surface ice fractures under tension, the cracks can penetrate the concrete substrate and propagate below the interface causing spalling. Salt can weaken the ice and promote these factures to occur.

Salt scaling likely results from a combination of different processes. Although the mechanism cannot be fully explained, the characteristics of salt scaling and the factors affecting scaling damage are well studied and understood. The water to cement ratio in the concrete, amount of cement in the concrete, amount of air entrained in the concrete, the surface finish of the concrete, and the addition of supplementary cementitious materials like fly ash, slag, and silica fume can be manipulated to improve resistance to salt scaling.[693]

Cement Paste Reactions

Chloride-based deicing chemicals that enter into chemical reactions with Portland cement paste can damage concrete. The reaction with $MgCl_2$ is more destructive to concrete than those with NaCl and $CaCl_2$. The strength of concrete is primarily derived from the reaction between cement and water. During hydration of Portland cement, calcium-silicate-hydrate (C-S-H) is formed. This provides strength and binding capacity in concrete. $MgCl_2$ reacts with C-S-H in the cement paste to produce $CaCl_2$ and a non-cementitious magnesium-silicate hydrate (M-S-H). M-S-H has a very low binding capacity. Its formation causes physical crumbing of the concrete. When $CaCl_2$ deicers are used on concrete containing dolomite aggregates, the $CaCl_2$ accelerates dedolomitization reactions to release magnesium that form additional M-S-H.[694]

During freeze-thaw cycles, chloride reacting with cement paste can cause decalcification of the cement. When calcium bearing minerals in concrete dissolve during freezing, the available calcium hydroxide in the pore solution reacts with chloride ions to form oxychloride crystals. This leads to calcium leaching from the concrete, which weakens it.[695]

Out of the three primary chloride-based deicers (NaCl, $CaCl_2$, and $MgCl_2$), $MgCl_2$ causes the most severe deterioration of concrete by damaging the strength of the cement matrix. NaCl has been shown to cause the least damage to the cement matrix in concrete structures.[696]

Alkali-Aggregate Reactions

Chloride compounds can also increase the occurrence of two alkali-aggregate reactions within concrete. The two reactions are alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR).

ASR is caused by chemical interactions between alkalis within the cement and silica in the aggregate. While the overall reaction is a complex process, ASR can result in the production of two gels. These gels are produced when alkali cations interact with reactive silica. An expansive gel can produce internal stresses within concrete that cause cracking. One gel produced in the ASR reaction is a calcium-alkali-silicate-hydrate that is not expansive. The other is an alkali-silica-hydrate that is expansive. Damage to concrete will not occur when only the non-expansive gel is formed; however, formation of both gels can lead to cracking. Exposure of concrete to NaCl can increase the pH of the concrete pore solution which creates more favorable conditions for ASR reactions. $CaCl_2$ and $MgCl_2$ have less effect on ASR reactions because they decrease the pH of the concrete pore solution.

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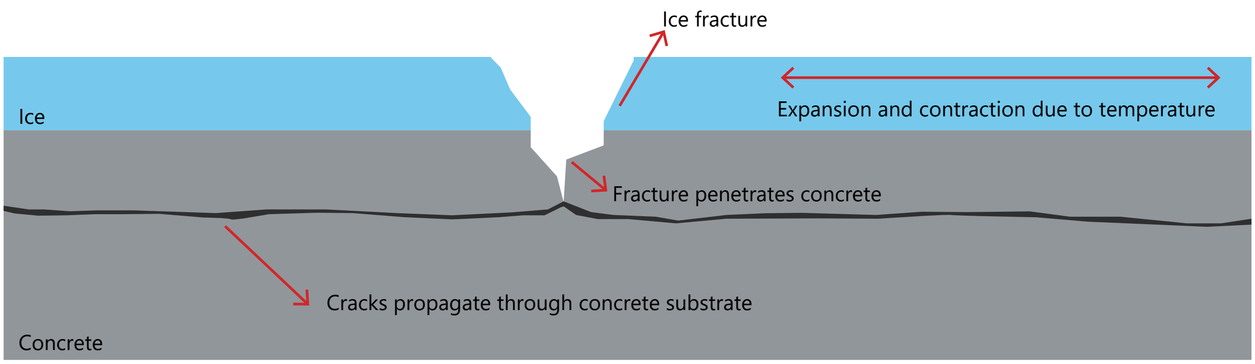
693 *G. Xu and X. Shi, "Impact of Chemical Deicers on Roadway Infrastructure: Risks and Best Management Practices," Chapter 11 in: X. Shi and L. Fu (editors),* Sustainable Winter Road Operations*, Wiley Blackwell, 2018*.

694 *Levelton Consultants Limited, 2007,* op. cit.

695 *G. Xu and X. Shi, 2018,* op. cit.

696 *Levelton Consultants Limited, 2007,* op. cit.

Figure 4.4
Glue Spall Mechanism



Source: SEWRPC

ACR occurs in concrete containing dolomite aggregates. In ACR, brucite ($Mg(OH)_2$) and calcite ($CaCO_3$) crystals are produced as a result of reactions between dolomite in the aggregate and portlandite in the cement. Crystal formation produces internal pressure in the concrete that can lead to fracturing. Exposure of dolomite-containing concrete to $CaCl_2$ and $MgCl_2$ can increase the amount of crystal formation because it makes additional Mg^{2+} and Ca^{2+} ions available to the reactions.[697]

Effects on Reinforcing Steel in Concrete

Steel is used in reinforced concrete to provide tensile and shear strength. Steel is a good material to reinforce concrete with because its rate of expansion with temperature is similar to that of concrete and the cement paste in concrete will conform to the surface of the steel as it dries, allowing stresses to be passed between the concrete and steel. The reinforcement is often accomplished by embedding steel bars (rebar) or meshes in the concrete.

Rebar corrosion caused by deicers compromises the strength and shortens the service life of concrete infrastructure. Under normal circumstances, the concrete cover provides physical and chemical protection for the reinforcing steel. The embedded steel is protected from corrosion by the high pH of the concrete pore solution. This produces an oxide/hydroxide film on the surface of the steel that act as a chemical barrier to corrosion.[698] Salt scaling, cement paste reaction, and alkali-aggregate reactions can compromise the concrete cover, allowing chloride, oxygen, and water to move through the concrete cover and reach the embedded steel.

Once the concrete has become compromised, chloride-induced steel corrosion discussed in section 4.2 can initiate in the steel rebars. The volume of the rust produced by corrosion is greater than that of the parent steel. Because of this, corrosion increases the internal pressure applied to the concrete by the rebar, eventually resulting in cracking of the concrete. Figure 4.5 shows a photo of a reinforced concrete beam damaged by rebar corrosion and Figure 4.6 illustrates this process.

Some deicers may cause greater corrosion of steel-reinforcement in concrete than others. $MgCl_2$ and $CaCl_2$ can decrease the pH of the cement paste. Since the embedded steel is chemically protected by the high pH of the concrete, this pH reduction can further increase the rate of rebar corrosion.[699] Additionally, laboratory testing has shown that $MgCl_2$ and $CaCl_2$ diffuse more quickly through concrete than NaCl. For example,

[697] *X. Shi, M. Akin, T. Pan, L. Fay, Y. Liu, and Z. Yang, "Deicer Impacts on Pavement Materials: Introduction and Recent Developments,"* The Open Civil Engineering Journal *3:16–27, 2009.*

[698] *Levelton Consultants Limited, 2007,* op. cit.

[699] Ibid.

the diffusion coefficient of $MgCl_2$ through Portland cement was 3 times greater than that of NaCl.[700,701] This suggests that $MgCl_2$ and $CaCl_2$ pose a greater risk of corrosion to reinforcing steel in concrete than NaCl; however, conflicting results have been reported in literature. A 2013 literature review concluded that most studies reported that $MgCl_2$ causes the greatest amount of damage to reinforced concrete while NaCl causes the least.[702] Conversely, a 2010 study concluded that NaCl causes the most damage to reinforced concrete followed by $CaCl_2$ and then $MgCl_2$.[703] More research may be needed to resolve this point.

Some concrete manufacturing techniques have been shown to improve concrete durability in the presence of deicers. Additives to the concrete mix such as fly ash and silica fume have been shown to reduce the permeability of concrete.[704] Reducing the water-to-cement ratio to below 0.4 has been shown to increase concrete strength.[705] Greater than 3 percent air entrainment has been shown to increase its resistance to frost damage.[706] Regular washing programs can also help to increase the life of concrete structures.

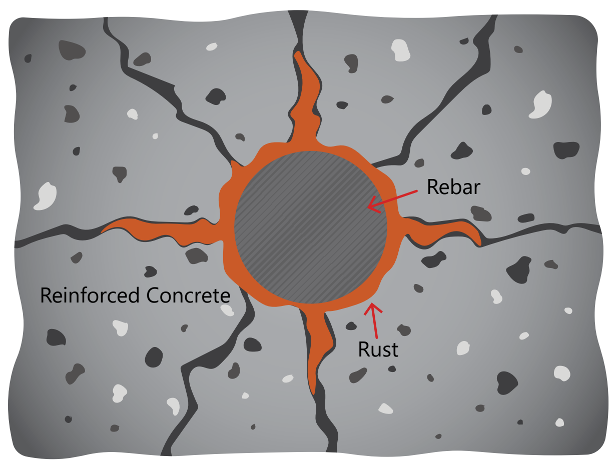
Effects on Asphalt Concrete

Asphalt concrete (asphalt) and Portland cement concrete (concrete) differ mainly in the binding material used: bitumen and Portland cement, respectively. Bitumen is a complex hydrocarbon material produced from petroleum production. It is an excellent binding material in asphalt because of its inherent adhesive properties. Portland cement is a fine powder material made from processing a mixture of limestone and clay. When Portland cement reacts with water, it hardens and becomes the binding material in concrete. Both asphalt and concrete are used in road and pavement construction. Asphalt is not used for constructing load-bearing members due to the viscosity of bitumen. This causes asphalt to undergo time dependent deformation under load especially at high temperatures.

Figure 4.5
Reinforced Concrete Beam Damaged by Rebar Corrosion

Source: WisDOT

Figure 4.6
Steel Reinforcement Corrosion Causing Concrete Damage



Source: SEWRPC

[700] *R. Kondo, M. Satake, and H. Ushiyama, "Diffusion of Various Ions into Hardened Portland Cement," paper presented at 28th General Assembly of the Cement Association of Japan, Tokyo, 1974.*

[701] *J. Deja and G. Loj, "Effects of Cations Occurring in the Chloride Solutions on the Corrosion Resistance of Slag Cementitious Materials," paper presented at Infrastructure Regeneration and Rehabilitation, Improving the Quality of Life Through Better Construction: A Vision for the New Millennium, Sheffield, United Kingdom, 1999.*

[702] *E.S. Sumsion and W.S. Guthrie, "Physical and Chemical Effects of Deicers on Concrete Pavement: Literature Review," Prepared for the Utah Department of Transportation Research Division by Brigham Young University, Department of Civil and Environmental Engineering, 2013.*

[703] *X. Shi, Y. Liu, M. Mooney, M. Berry, B. Hubbard, and T.A. Nguyen, "Laboratory Investigation and Neural Networks Modeling of Deicer Ingress into Portland Cement Concrete and its Corrosion Implications,"* Corrosion Reviews, *28:105–154, 2010.*

[704] *Massachusetts Department of Transportation, 2017,* op. cit.

[705] *Levelton Consultants Limited, 2007,* op. cit.

[706] *G. Xu and X. Shi, 2018,* op. cit.

As with concrete, asphalt can be affected by deicers; however, due to the physical and chemical differences described above, the mechanisms are different from those that affect concrete. The effects of salt on asphalt are very complex and not fully understood. In general, studies show that at low temperatures deicers compromise its fatigue resistance properties and reduce its rutting resistance by decreasing the stiffness of asphalt.[707,708] In particular, chloride-based deicers can weaken the bond between bitumen and aggregate, shortening the service life of the asphalt pavement.[709]

Alternative Non-Chloride Deicers

Other non-chloride-based deicer compounds also exist. These include calcium magnesium acetate (CMA), potassium acetate, potassium formate, sodium acetate, sodium formate, and urea. These are widely used as alternatives to chloride-based deicers in airports because of their reduced risk of corrosion to aircraft parts; however, their higher costs limit their use on roadways.[710] Acetates and organic deicers have been shown to cause deterioration of concrete pavements through different mechanisms than chloride-based deicers.[711] They can also contribute biochemical oxygen demand to receiving waters which can affect water quality.[712] Non-chloride deicers are not the focus on this study and will not be discussed in detail in this report. For further discussion on these and other non-chloride deicers, see SEWRPC Technical Report No. 66, *State of the Art of Chloride Management* (in development).

4.4 CHORIDE IMPACTS TO MOTOR VEHICLES AND INFRASTRUCTURE

Motor vehicle and infrastructure corrosion and deterioration induced by chloride road salts have been widely observed and documented since road salt use became widespread during the 1960s. Due to growing concerns over the impacts of deicing salt usage, the mechanisms through which chloride causes corrosion of infrastructure and motor vehicles have been extensively researched. While the quantitative impacts of deicers to infrastructure and the built environment are difficult to estimate, several studies have attempted to estimate the economic costs of damages caused by deicers. The results of these studies are summarized below. It is worth noting, however, that due to the age of some of these studies and the difficulty in accurately estimating specific costs associated with damages caused by road salt, the values presented should be interpreted with care.

Impacts to Motor Vehicles

The impact of corrosion on motor vehicles is one of the better studied topics. Several major studies have been conducted to estimate the total costs from vehicle corrosion and a few studies have attempted to estimate those costs attributable to roadway deicing only. The economic costs are first presented as stated in the original studies. These costs are then compared after computing the per vehicle unit costs and adjusting them for inflation to June 2021 dollars. When possible, the estimated total costs for the Region are also presented.

Impacts from All Sources of Corrosion

Table 4.1 shows nationwide estimated costs of corrosion from two studies. In a 1978 study conducted for the National Bureau of Standards (NBS), Battelle Columbus Laboratories (BCL) estimated the total direct and indirect annual cost of metallic corrosion across all industries in the U.S. to be $82 billion.[713] These costs

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[707] *X. Yu, Y. Wang, Y. Luo, and L. Yin, "The Effects of Salt on Rheological Properties of Asphalt after Long-term Aging,"* The Scientific World Journal*, pages 1–10, 2013.*

[708] *L. Wang, Y. Cui, Z. Liu, and W. Huang, "Influence of Salt Freezing on Asphalt Mortar's Stiffness Modulus," paper presented at the International Conference on Transportation Engineering, American Society of Civil Engineers, Chengdu, China, 2013.*

[709] *D. Feng, J. Yi, D. Wang, and L. Chen, "Impact of Salt and Freeze-Thaw Cycles on Performance of Asphalt Mixtures in Coastal Frozen Regions of China,"* Cold Regions Science and *Technology, 62:34-41, 2010.*

[710] *Levelton Consultants Limited, 2007,* op. cit.

[711] *G. Xu and X. Shi, 2018,* op. cit.

[712] *National Academies of Sciences, Engineering, and Medicine, "Formulations for Aircraft and Airfield Deicing and Anti-Icing: Aquatic Toxicity and Biochemical Oxygen Demand," Washington D.C., The National Academies Press, 2009.*

[713] *Battelle Columbus Laboratories, "Economic Effects of Metallic Corrosion in the United States," Appendix B, NBS Special Publication 511-2, SD Stock No. SN-003-003-01926-5, 1978.*

accounted for 4.9 percent of the U.S. Gross National Product (GNP) in 1975. The study attributed about $31 billion of these costs to the automotive industry. More specifically, the annual cost of corrosion protection for new privately-owned vehicles was estimated to be $937 million nationwide. The costs of corrosion-related maintenance and repairs to privately-owned vehicles was estimated to be $5 billion per year. These estimates were all given in 1975 dollars.

Table 4.1
Cost Estimates of Metallic Corrosion in the United States

	Annual Direct and Indirect Cost of Corrosion (billion dollars)	
	1978 BCL Study[a]	1995 BCL Update[b]
All Industries		
Total	82.0	296.0
Avoidable	33.0	104.0
Automotive Industry		
Total	31.4	94.0
Avoidable	23.1	65.0

[a] *Reported in 1975 dollars*

[b] *Reported in 1995 dollars*

Source: Battelle Columbus Laboratories, Economic Effects of Metallic Corrosion in the United States, 1978 and Update, 1995

The BCL/NBS study was updated in 1995 (see Table 4.1).[714] The update attempted to account for the significant improvements to anticorrosion technology and practices that had occurred since the original study was published, particularly those in the automotive industry. Implementation of stainless steel, coated metal, and protective finishes in many industries had reduced the costs due to corrosion in the U.S. The study noted though that certain corrosion costs had increased due to expanded regulations. It cited regulations prohibiting the use of certain methods of corrosion protection that were implemented due to their negative impacts to public safety and the environment. The updated study estimated metallic corrosion costs in 1995 to be $296 billion per year across all industries. This amount accounted for economic growth in the U.S. and represented about 4.2 percent of GNP in 1995. Approximately $94 billion or 32 percent of the costs were attributed to motor vehicle corrosion.[715] The 1995 study update also found that 35 percent of total metallic corrosion costs could be avoided through broader application of corrosion-resistant materials and best practices. This was lower than the 40 percent that was estimated in the original 1978 study.

A few other studies attempted to obtain more detailed estimates of costs associated with motor vehicle corrosion. In 1991, the Transportation Research Board (TRB) published a study that estimated corrosion protection costs in newly manufactured vehicles. The cost estimates ranged between $3.8 billion and $12.3 billion with an average of $7.7 billion (1989 dollars).[716] In 1998, an amendment to the Transportation Equity Act of the 21st Century mandated that a comprehensive study of the economic cost of corrosion be conducted. The Federal Highway Administration (FHWA) completed the required study in 2002.[717] This study estimated that the total annual direct cost of corrosion across all industry sectors of the U.S. economy was $276 billion, representing 3.1 percent of the 1998 U.S. Gross Domestic Product (GDP). The portion of this cost attributable to corrosion of motor vehicles was estimated to be $23.4 billion (1999 dollars). This cost consisted of $2.5 billion for new vehicle corrosion protection materials, $6.5 billion for repairs and maintenance to vehicles due to corrosion, and $14.4 billion for vehicle depreciation related to corrosion.[718,719]

[714] *Battelle Columbus Laboratories, "Economic Effects on Metallic Corrosion in the United States-Update," 1995.*

[715] *J.R. Davis, "The Effect and Economic Impact of Corrosion," Chapter 1 in: J.R. Davis,* Corrosion: Understanding the Basics, *ASM International, January 2000.*

[716] *Transportation Research Board, "Highway Deicing: Comparing Salt and Calcium Magnesium Acetate," National Research Council, Washington D.C., 1991.*

[717] *G.H. Koch, M.P.H. Brongers, N.G. Thompson, Y.P. Virmani, and J.H. Prayer, "Corrosion Cost and Preventative Strategies in the United States," U.S. Department of Transportation, Federal Highway Administration, NACE International, Report FHWA-RD-01-156, 2002.*

[718] *J.T. Johnson, "Corrosion Costs of Motor Vehicles," Appendix N in: G.H. Koch, M.P.H. Brongers, N.G. Thompson, Y.P. Virmani, and J.H. Prayer, "Corrosion Cost and Preventative Strategies in the United States," U.S. Department of Transportation, Federal Highway Administration, NACE International, Report FHWA-RD-01-156, 2002.*

[719] *The motor vehicle numbers used in the study include automobiles and trucks, and do not include motorcycles and trailers.*

To facilitate comparisons among the studies above, the costs were expressed as per vehicle costs and adjusted for inflation using the U.S. Bureau of Labor Statistics Consumer Price Index (CPI). Table 4.2 summarizes the corrosion per vehicle costs. The estimated per vehicle unit costs for both new vehicle corrosion protection and used vehicle repairs and maintenance were lower in the 2002 FWHA study than those from the two earlier studies. The difference was attributed to the successful implementation of corrosion management strategies and the application of new anticorrosion technologies in the automotive industry.[720] However, it is worth noting that the studies differ in methodology and that any corrosion cost comparisons should be used with care.

There are approximately 1.5 million[721] available automobiles and trucks registered in the seven counties served by SEWRPC (Region). Using the estimated figures from the 2002 FHWA study, the annual total cost of vehicle repairs and maintenance due to corrosion would be $79 million (2021 dollars), and the annual cost of vehicle depreciation due to corrosion would be $268 million (2021 dollars) in the Region.

Impacts from Corrosion Due to Roadway Deicing

The studies discussed in the previous section examined the cost of vehicle corrosion from all sources. In a literature review of studies that were conducted in the late 1960s and early 1970s, Jones and Jeffery concluded that approximately 50 percent of vehicle corrosion can be attributed to the use of road salt in snow impacted regions.[722] Based on the findings of the 2002 FHWA study, this would suggest that the total annual direct cost of vehicle corrosion including protection, repairs, and depreciation in the U.S. due to road deicing could be approximately $120 per vehicle (2021 dollars).[723] The estimated total annual cost for the Southeastern Wisconsin Region could be on the order of $180 million (2021 dollars).

Several studies have attempted to estimate the costs of vehicle depreciation resulting from corrosion caused by road salt (see Table 4.3). An early study carried out for the U.S. Environmental Protection Agency (USEPA) in 1976 estimated that the annual cost of vehicle depreciation due to road salt was approximately $1.4 billion or $14 per vehicle nationwide (1973 dollars).[724] A 1991 study by Menzies estimated the annual deprecation cost due to road salt by comparing vehicle deprecation in regions affected by both marine environments and road deicing to regions only affected by marine environments.[725] This study estimated that the annual per vehicle cost of depreciation due to road salt was $17 (1991 dollars). The 2002 FHWA study by Johnson employed a method similar to the study by Menzies. This study estimated an annual per vehicle depreciation cost due to road salt of $32 (1999 dollars).[726,727] Based on this estimate, the total vehicle depreciation cost due to road salting in the U.S. in 1999 would have been $3.8 billion per year.[728] Based on the estimated cost in given in the 2002 FHWA study, the total annual vehicle deprecation cost due to road salt in the Southeastern Wisconsin Region could be approximately $78 million (2021 dollars).

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[720] *G. Koch, J. Varney, N. Thompson, O. Moghissi, N. Gould, J. Payer, "International Measures of Prevention, Application, and Economics of Corrosion Technologies Study," NACE International IMPACT, 2016.*

[721] *2021 Wisconsin DOT Vehicle Registration information and SEWRPC estimates.*

[722] *P.H. Jones and B.A. Jeffrey, "Environmental Impact of Road De-icing," in F.M. D'Itri (editor),* Chemical Deicers and the Environment*, Boca Raton, Florida: Lewis Publishing, pages 1-97, 1992.*

[723] *Calculation used the estimate from the 2002 FHWA study that 60 percent of approximately 200 million vehicles in the U.S. at the time of publication were in the snow impacted regions of the U.S. The U.S. Bureau of Labor Statistics Consumer Price Index for June of each year was also used to adjust for inflation.*

[724] *D.M. Murray and W.F.W. Ernst, "An Economic Analysis of the Environmental Impact of Highway Deicing," United States Environmental Protection Agency, EPA-600/2-76-105, 1976.*

[725] *T.R. Menzies, "National Cost of Motor Vehicle Corrosion from Deicing Salts," Corrosion 91/399, Houston TX, NACE International, 1991.*

[726] *J.T. Johnson, 2002,* op. cit*.*

[727] *These estimates do not consider the economic differences between the different regions of the U.S. being compared nor do they consider the possible movement of vehicles between regions at the point of sale.*

[728] *Johnson estimated 60 percent of approximately 200 million vehicles in the U.S. at the time of his study publication are in the snow impacted regions of the U.S., therefore $32/vehicle x 60% x 200 million vehicles = $3.8 billion.*

Table 4.2
Annual Cost Estimates of Vehicle Corrosion from All Sources

	Annual Cost Per Vehicle (dollars)					
	1978 BCL Study		1991 TRB Study		2002 FHWA Study	
	1975 dollars	2021 dollars[a]	1989 dollars	2021 dollars[a]	1999 dollars	2021 dollars[a]
New Vehicle Corrosion Protection	140 to 210	710 to 1,064	250 to 800	547 to 1,751	150	245
Used Vehicle Corrosion Repairs and Maintenance	46	236	--	--	32	53

[a] *Adjusted for inflation using the U.S. Bureau of Labor Statistics Consumer Price Index for June of each year*

Source: Battelle Columbus Laboratories, Economic Effects of Metallic Corrosion in the United States, 1978; Transportation Research Board, Comparing Salt and Calcium Magnesium Acetate, 1991; Federal Highway Administration, Corrosion Cost and Preventative Strategies in the United States, 2002

Table 4.3
Annual Cost Estimates of Vehicle Deprecation Due to Corrosion by Road Salt

	Annual Cost Per Vehicle (dollars)					
	1976 EPA Study		1991 Menzies Study		2002 FHWA Study	
	1973 dollars	2021 dollars[a]	1991 dollars	2021 dollars[a]	1999 dollars	2021 dollars[a]
Depreciation Due to Corrosion by Road Salt	14	86	17	34	32	52

[a] *Adjusted for inflation using the U.S. Bureau of Labor Statistics Consumer Price Index for June of each year*

Source: Environmental Protection Agency, An Economic Analysis of the Environmental Impact of Highway Deicing, 1976; Menzies T.R., National Cost of Motor Vehicle Corrosion from Deicing Salts, 1991; Federal Highway Administration, Corrosion Cost and Preventative Strategies in the United States, 2002.

The TRB study published in 1991 also estimated the per vehicle cost of corrosion protection as a direct response to road salt.[729] Based on survey of vehicle manufacturers, the estimate was between $125 and $250 per new vehicle (1989 dollars). When adjusted for inflation, this cost is between $274 and $547 per new vehicle (2021 dollars). Since vehicle registration data for newly manufactured vehicles are not available for the Region, the costs of corrosion protection due to roadway deicing for the Study area were not estimated.

Summary of Impacts to Motor Vehicles

National interest in quantifying the economic impacts of corrosion from all sources and corrosion due to road salt has led to several studies being done since the 1960s with the latest comprehensive study being completed in 2002. These studies concluded that corrosion affecting all industries carries a significant cost to the U.S. economy, which is equivalent to several percentage points of U.S. GDP. Nevertheless, costs due to corrosion have noticeably decreased, particularly in the automotive industry. Between 1975 and 1999 costs of new vehicle corrosion protection and used vehicle corrosion repair and maintenance from all sources of corrosion decreased by a factor of more than three (see Table 4.2). Similarly, between 1973 and 1999 vehicle depreciation costs due to corrosion from road salt also saw a significant reduction (see Table 4.3). These cost reductions can be attributed to improvements in the corrosion management techniques and implementation of anticorrosion technology in the automotive industry. Despite these improvements, the costs of motor vehicle corrosion from road salting are still appreciable. Based on the 2002 FHWA study and the 1992 Jones and Jeffery estimate, the total annual direct cost of vehicle corrosion due to road salt in the Southeastern Wisconsin Region is on the order of $180 million (2021 dollars). This estimate is based on studies conducted over 20 years ago. New corrosion protection technologies have likely been implemented since that time and now, the cost of vehicle corrosion may be lower. New studies would be needed to assess the current state of motor vehicle corrosion due to road salt with greater accuracy.

[729] *Transportation Research Board, 1991* op. cit.

Impacts to Bridges

Two major studies have been conducted to evaluate the cost of corrosion damages to highway bridges in the U.S. The 2002 FHWA study previously discussed included estimated bridge costs from all sources of corrosion, and the previously discussed 1991 TRB study estimated bridge damage costs due to road salt.[730,731] Costs from both studies are first presented as stated in the original studies. Following this, the total estimated cost of damages to highway bridges in the Region due to road salt is presented in 2021 dollars.

Impacts from All Sources of Corrosion

According to the 2022 National Bridge Inventory (NBI) dataset,[732] there are currently over 620,000 highway bridges in the United States. Reinforced concrete bridges, including conventional and prestressed concrete, account for 428,000 or 69 percent of these bridges. Metal bridges, including those made from steel, aluminum, or iron account for 175,000 or 28 percent of the highway bridges in the U.S. Approximately 11 percent of all highway bridges are in poor structural condition.[733] Structural damages are primarily attributed to corrosion of metal and metal reinforcement in concrete.[734] As part of the 2002 FHWA study on the economics of corrosion, Yunovich estimated the annual direct cost of corrosion of highway bridges to be between $6.4 billion and $10.2 billion (1999 dollars).[735] These costs included the costs of replacing structurally deficient bridges ($3.8 billion), replacing and maintaining concrete bridge decks ($1.1 billion to $2.9 billion), replacing and maintaining concrete substructures and superstructures ($1.1 billion to $2.9 billion), and painting metal bridges ($0.5 billion). Additionally, life-cycle analyses estimated that the indirect costs of bridge corrosion due to lost productivity and traffic delays are more than 10 times that of the direct cost of corrosion. In the past two decades, progress has been made to improve the percentage of deficient bridge structures in the U.S. In year 2000, 18 percent of highway bridges were rated as being in poor or worse condition. Today, that number has dropped to 11 percent.[736] The median age of bridges in the U.S continues to increase. Between 2000 and 2022, the median age of American highway bridges increased from 35 years to 44 years. As the bridge infrastructure continues to age, additional bridge deterioration would be expected. In addition, the costs of repairing and replacing deteriorating bridge infrastructure will increase in the future.

Impacts from Corrosion Due to Roadway Deicing

Not all damage to bridges can be attributed to road salting; however, the effects of salt on bridge infrastructure are well known. During the 1950s and 1960s, many newly constructed bridge decks on Interstate highways used steel reinforcement positioned two inches below the concrete surface. Due to the shallow depth of the embedded steel, corrosion was observed soon after construction in regions where road salt was used. A few studies have attempted to estimate the costs of bridge damage associated with road salting. The 1991 TRB study previously discussed made the most recent comprehensive assessment of bridge damage costs.[737] This study estimated the total annual direct costs of bridge damage from road salt in the U.S. as being between $250 million and $650 million (1991 dollars). Half of the total cost were attributed to salt damage to bridge decks. Localized damage such as potholes often form after a portion of the bridge deck has been critically contaminated with chloride. While patching is commonly used to repair localized damage to decks, deterioration could continue after this type of damage despite patching repairs or discontinued use of road salt. It is estimated that in regions with heavy road salt use, decks unprotected by special waterproofing or

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[730] *G.H. Koch, M.P.H. Brongers, N.G. Thompson, Y.P. Virmani, and J.H. Prayer, 2002,* op. cit.

[731] *Transportation Research Board, 1991,* op. cit.

[732] *U.S. Federal Highway Administration, National Bridge Inventory, U.S. Department of Transportation, www.fhwa.dot.gov/bridge/nbi/ascii.cfm, accessed on July 28, 2022.*

[733] *Structural Evaluation rating of 4 or lower within the NBI dataset.*

[734] *G.H. Koch, M.P.H. Brongers, N.G. Thompson, Y.P. Virmani, and J.H. Prayer, 2002,* op. cit.

[735] *M. Yunovich, N.G. Thompson, T. Balvanyos, and L. Lave, "Corrosion Costs of Highway Bridges," Appendix D in: G.H. Koch, M.P.H. Brongers, N.G. Thompson, Y.P. Virmani, and J.H. Prayer, "Corrosion Cost and Preventative Strategies in the United States," U.S. Department of Transportation, Federal Highway Administration, NACE International, Report FHWA-RD-01-156, 2002.*

[736] *Calculated based on the U.S. Federal Highway Administration National Bridge Inventory dataset from 2000 and 2022.*

[737] *Transportation Research Board, 1991,* op. cit.

sealants will reach a critical chloride contamination level within 10 to 15 years after construction.[738] Since 1984, the FHWA has required that corrosion protection be installed on all new bridges constructed with Federal assistance in states where road salt is used. Today, most bridges built in snow impacted regions use corrosion protection such as epoxy-coated reinforcing steel, waterproofing membranes, concrete covers or overlays, or catalytic protection. It should be noted that nearly 60 percent of all highway bridges in the U.S. in use today were built prior to 1984. Some of those bridges have already had their decks replaced, but a significant portion of them still require deck replacement.[739] The 1991 TRB study estimated that the total annual nationwide cost of repairing salt damage to bridge decks would be between $50 million and $200 million.[740] This study also estimated that the annual nationwide cost of providing deck protection to bridges would be between $75 million and $125 million. The TRB study committee also estimated that the annual costs of repairing other bridge components in the U.S. including grid decks, joints, drainage systems, and structural components such as bearings, steel framing and supports, and concrete support structures fall within the same range as repairing bridge decks, about $125 million to $325 million per year.

According to the 2022 NBI dataset, southeastern Wisconsin contains about 2,000 highway bridges.[741] Bridge conditions in the Region are generally better than the nationwide average. Only about 6 percent of bridges in the region have structural conditions rated poor or worse. The median age of highway bridges in southeastern Wisconsin is approximately 40 years. Based on the 1991 TRB study, the annual direct cost of damage to highway bridges due to road salt use in the Region would be between approximately $800,000 to $2.1 million (1991 dollars). When adjusted for inflation, the annual damage estimate range becomes $2.4 million to $6.3 million (2021 dollars).[742]

Summary of Impacts to Bridges

Since only a few studies have attempted to estimate road salt damage costs to bridges, no temporal trend can be determined. Two competing factors impact bridge damage trends: implementation of anticorrosion measures and the aging bridge infrastructure in the U.S. The implementation of corrosion protection techniques and technologies are extending the useful life of bridges. Advances in concrete construction, use of anticorrosion materials, and implementation of washing programs all potentially reduce damage due to road salt. By contrast, the current average ages of highway bridges in the U.S. and southeastern Wisconsin are 44 years and 40 years, respectively. These average bridge ages have also increased over time. As bridge infrastructure deterioration increases due to aging, bridges will become more susceptible to damage from road salt. Based on the 1991 TRB study, the total annual damages to highway bridges in the Region are estimated to be between $2.4 million and $6.3 million (2021 dollars). This estimate is based on studies conducted over 30 years ago. New studies are needed to assess the current state of bridge infrastructure damage with greater accuracy.

Impacts to Other Highway Components

The largest component of highway infrastructure is roadway pavement. Pavement damage caused by salt scaling during freeze-thaw cycles is perhaps the most well-known impact of road salt on roadways. Poor quality pavement produced by improper curing, finish, air entrainment, or water content have in the past caused rapid deterioration of roadways in northern states. In recent decades, the effects of road salt on concrete and asphalt have become better understood. Pavement damage caused by road salting is no longer as serious a concern as it once was.[743] Today, quality control of pavement construction has vastly improved. Improved practices like the use of air entrainment, the reduction of water to cement ratios, the use of sealants, and the use of additives such as fly ash and silica fume have resulted in more durable pavement in snow impacted regions.[744] The durability of concrete expansion joints remains a concern for

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[738] Ibid.

[739] *U.S. Federal Highway Administration, 2022,* op. cit.

[740] *Transportation Research Board, 1991,* op. cit.

[741] *U.S. Federal Highway Administration, 2022,* op. cit.

[742] *Inflation adjustment was based on the Engineering News-Record Construction Cost Index of 1991 and 2021.*

[743] *Transportation Research Board, 1991,* op. cit.

[744] *Massachusetts Department of Transportation, 2017,* op. cit.

concrete pavement. Premature deterioration has been observed at the joints where the pavement is more accessible to moisture, debris, and chlorides. More frequent maintenance and the use of sealants have been proposed to mitigate this concern.[745]

The 1991 TRB study also assessed salting impacts to highway drainage systems, highway fixtures and accessories, and sidewalks and driveways. The study concluded that salt was not a significant factor affecting the durability of these highway components. Other factors such as traffic stress, normal wear, erosion, and soil settlement had the greatest effect on the deterioration of these roadway components.

Based on limited available information, the 1991 TRB committee concluded that road salt is not a major factor for damage to pavements and other highway components. The TRB roughly estimated a total annual nationwide cost of $100 million (1991 dollars).[746]

Impacts to Buildings

Road salt can cause deterioration of buildings through the same mechanisms as those through which it impacts bridges and roads. The lower portions of buildings located along high traffic roads where road salts are applied may be particularly vulnerable. Their exteriors can deteriorate with long term exposure to road salt. Normal vehicle traffic and winter snow and ice control vehicles can splash water and salt onto building walls, initiating chloride induced damage to building structures. It is likely that this kind of damage is uncommon in the U.S. Most municipalities have minimum building setback ordinances that prevent buildings from being constructed immediately next to roadways. Building damage caused by deicing operations might occur in some densely developed city centers. The extent of such damage is largely unknown, and no estimates are available that quantify the costs of this sort of damage in the U.S. It is likely that the costs related to this type of damage from road salt are relatively small.

Road salt impacts to parking structures, however, may be more significant in regions where deicing is prevalent. During snow seasons, vehicles can transport snow and salt into parking structures. The water and chlorides from melted snow can reach exposed metal components and seep into cracks in the reinforced concrete and the deterioration process would be similar to that of bridges. When poorly maintained, parking structures can quickly lose their serviceability. The 1991 TRB study previously discussed estimated that between 50 and 150 parking structures in the U.S. would require rehabilitation annually due to salt damage.[747] The annual cost of this would be between $50 million and $150 million (1991 dollars). This figure might be lower today as more parking structures are being built with protective systems against chloride degradation such as sealants, membranes, coated reinforcing steel, and better drainage systems. The TRB estimated that the nationwide cost of including salt corrosion protection on the approximately 200 new parking garages built each year would be approximately $25 million per year (1991 dollars).

Impacts to Water Supply Infrastructure

Elevated levels of chloride in drinking water have the potential to corrode water distribution systems, reducing the life of drinking water infrastructure, causing leaks, and degrading drinking water quality. Specifically, the release of lead and copper resulting from the corrosion of water distribution pipes is of major concern. Several studies have found links between high chloride concentrations in finished drinking water and the corrosion of water mains and service lines.[748,749,750] During the 2014 Flint, Michigan water utility

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[745] *P. Suraneni, J. Monical, E. Unal, Y. Farnam, C. Villani, T.J. Barrett, and W.J. Weiss, "Performance of Concrete Pavement in the Presence of Deicing Salts and Deicing Salt Cocktails," Indiana Department of Transportation and Purdue University, Report FHWA/IN/JTRP-2016/25, 2016.*

[746] *Transportation Research Board, 1991,* op. cit.

[747] *Transportation Research Board, 1991,* op. cit.

[748] *American Water Works Association,* Internal Corrosion of Water Distribution Systems*, Second edition, AWWA Research Foundation/DVGW-TZW, Denver, CO, 1996.*

[749] *M. Edwards and S. Triantafyllidou, "Chloride-to-Sulfate Mass Ratio and Lead Leaching to Water,"* Journal of the American Water Works Association, *99:86-109, 2007.*

[750] *C.K. Nguyen, B.N. Clark, K.R. Stone, and M.A. Edwards, "Role of Chloride, Sulfate, and Alkalinity on Galvanic Lead Corrosion,"* Corrosion*, 67, doi: 10.5006/1.3600449, 2011.*

crisis where high lead levels were found in the distribution system, elevated chloride concentrations and chloride-sulfate mass ratio (CSMR) were also observed. [751]

In a 2018 paper, researchers examined trends in chloride concentrations and CSMR in surface waters across the continental U.S.[752] The study found that during the period 1992 through 2012, both chloride concentrations and CSMR increased. The trend was especially strong for urban areas in cold-weather months, suggesting that road salt use could be the main contributor of chloride. Since typical drinking water treatments do not remove chlorides, high chloride concentrations in the source water would be retained in the finished water. In the study, the researchers also found an association between the chloride levels and exceedances of the lead action level (ALEs) in drinking water system monitoring samples. Statistical correlation was observed between the increase in surface water CSMR and the increase in the occurrences of lead ALEs, leading to a potential connection between the quality of the source water and corrosion of water distribution systems.

Another paper examined the extent of chloride concentrations in groundwater and its impact on private well infrastructure in the State of New York.[753] Using data from citizen science sampling, the study found that chloride concentrations in private wells were highest downgradient of road salt storage facilities and within 30 meters (100 feet) of major roadways. Using bench-scale testing, the study found that increased chloride levels in synthetic well water increased galvanic corrosion of wells and home plumbing. Private wells are especially susceptible to this type of corrosion since galvanized iron is still commonly used in well construction. Based on modeling results, the study suggested that potentially two percent of the private wells in the State of New York could be impacted by road salt storage facilities and 24 percent could be impacted by road salt applications.

Chloride impacts to water supply infrastructure is an emerging area of study. The extent of the impact is still not fully understood. More research is needed on the effects of chloride on both private wells and municipal water supply infrastructure.

Chlorine and Chloride Distinctions in Drinking Water Supply

In the context of water supply infrastructure, it is important to clarify the distinction between chlorine and chloride. Chlorine is a chemical used in drinking water treatment plants to disinfect drinking water by killing harmful parasites, bacteria, and viruses. Chlorine is often introduced to drinking water as sodium hypochlorite (NaClO). When NaClO is dissolved in water, chlorine is released. The use of chlorine in water treatment is an important step to provide safe drinking water. After the initial chlorination of drinking water at the treatment plant, a low level of residual chlorine is typically maintained in the drinking water distribution system to safeguard against water contamination in route to the end user. The residual chlorine present in water distribution system is chemically very different from chloride. Chloride, which is the negatively charged ionic form of chlorine, enters the drinking water distribution system due to the dissolution of chloride salts in the environment. While chloride ions corrode water distribution pipes and promote the release of lead and copper that are harmful to human health, chlorine residuals do not.

Impacts to Power Distribution Systems

Some anecdotal information suggests that road salt can degrade insulators surrounding electrical wiring and equipment. When road salt is used, some salt can become airborne (see Chapter 2 of this report). This salt can be deposited and accumulate on electrical structures and suspended wiring. As the chlorides degrade the insulators around the electrical equipment, the insulators can become slightly conductive resulting in current leaks that can cause current disruption, shorting of transmission lines, and fires on wooden electric poles.[754] In 2001, Wisconsin Electric in Milwaukee indicated that during the 2000 winter season, about 15

[751] *K.J. Pieper, M. Tang, and M.A. Edwards, "Flint Water Crisis Caused by Interrupted Corrosion Control: Investigating "Ground Zero" Home,"* Environmental Science and Technology, *51:2,007–2,014, 2017.*

[752] *E.G. Stets, C J. Lee, D A. Lytle, and M.R. Schock. "Increasing Chloride in Rivers of the Conterminous U.S. and Linkages to Potential Corrosivity and Lead Action Level Exceedances in Drinking Water,"* Science of the Total Environment, *613–614:1,498–1,509, 2018.*

[753] *K.J. Pieper, M. Tang, C.N. Jones, S. Weiss, A. Greene, H. Mohsin, J. Parks, and M.A. Edwards, "Impact of Road Salt on Drinking Water Quality and Infrastructure Corrosion in Private Wells,"* Environmental Science & Technology, *52, 14,078-14,087, 2018*

[754] *Levelton Consultants Limited, 2007,* op. cit.

pole fires and many power outages occurred after the salting of roads.[755] More recently, power outages in Nova Scotia, Canada were also blamed on salt contamination both from sea water and from road salt.[756]

Concerns have also been expressed about potential impacts of chloride salts on underground utility lines and electric power equipment. Several power utilities in the U.S. have claimed that high chloride contamination of soil from road salts have caused short circuits and burnouts of underground electric power transformers, switches, and service cables.[757] The Electric Power Research Institute, however, has stated that the likelihood of corrosion damage to underground electrical utilities due to high salt concentrations is low since most buried service cables are well insulated.[758] It should be noted, though, that issues can arise in older electrical systems that are not well insulated.[759]

No formal studies exist regarding road salt impacts to power distribution systems. All the available information is anecdotal. More research is needed to determine the frequency, mechanism, and magnitude of the potential issue.

Impacts to Railway Traffic Control Signaling

Anecdotal information is also available regarding the impact of road salt on railroad traffic control devices. Train detection on modern railways often relies on transmission of electrical signals through the rails. The presence of trains interrupts electric circuits established on different sections of rail tracks. This information is used to detect the locations and speeds of trains. When a train is detected, traffic warning signals and gates are activated. Signal transmission through the rails can be impacted by ionic salt solutions due to their effect on electrical conductivity. Triggering of train signals without the presence of a train and early initiation of train signals has been attributed to the presence of road salt at railroad crossings.[760] Some cases of train signals failing to activate have also been attributed to road salt usage. In 2011, two vehicles collided with a stopped train in Chicago resulting in serious injuries because the warning signals and gates were not activated. The incident was attributed to an electrical shorting caused by road salt.[761]

The extent and severity of the impacts of road salt on railway traffic signaling is currently unknown. Only cases with extremely high concentrations of road salt solution have been observed to affect railway traffic control signaling. Some limited field tests conducted by state departments of transportation have failed to reproduce the observed traffic signaling issues.[762]

Benefit-Cost of Road Salting

Road salting for snow and ice maintenance provides significant benefits to roadway safety and prevents economic losses from road closures. In a 1992 study by Marquette University, researchers analyzed accident statistics and economic costs related to snow and ice operations in the states of New York, Illinois, Minnesota, and Wisconsin.[763] The study compared accidents during winter storm events before and after road salt was applied. It found that after road salt was applied, injuries caused by accidents and the associated costs were reduced by 88 percent for two-lane highways and 85 percent for freeways. The average cost of an

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755 *Pure Power, "Road Salt Causes Power Outages," March 1, 2001, www.csemag.com/articles/road-salt-causes-power-outages, accessed September 12, 2022.*

756 *Canada Broadcasting Corporation, "The Science Behind the Salty Towers Causing Nova Scotia Power Outages," January 13, 2018, www.cbc.ca/news/canada/nova-scotia/salt-air-power-lines-nova-scotia-electricity-1.4483369, accessed September 12, 2022.*

757 *Transportation Research Board, 1991,* op, cit.

758 Ibid.

759 Ibid.

760 *Levelton Consultants Limited, 2007,* op. cit.

761 *CBS News Chicago, "Road Salt to Blame for Railroad Gate Failure?," February 15, 2011, www.cbsnews.com/chicago/news/road-salt-to-blame-for-railroad-gate-failure/, accessed September 12, 2022.*

762 *Levelton Consultants Limited, 2007,* op. cit.

763 *D.A. Kuemmel and R.M. Hanbali, "Accident Analysis of Ice Control Operations," Transportation Research Center, Marquette University, 1992.*

accident after road salt was applied was reduced by 10 percent for two-lane highways, and by 30 percent for freeways. The study estimated that $1 spent on direct winter maintenance operation can provide $7 in direct economic benefits for two-lane highways and $4 for freeways. The direct economic benefits computed by the study included cost savings from reduction in accidents, travel time, and vehicle fuel consumption. It should be noted that the observed reduction in accidents should not be fully attributed to winter maintenance operations. The reduction in traffic volume as winter storms progress can explain some of the reduction in accidents. Later studies documented that the economic benefits of road salt usage can be much more complex than was presented in the Marquette study. In a 2006 snowstorm crash analysis study, the authors noted that the benefits of road salting can vary significantly depending on the type and severity of winter storms, driver behavior, pavement conditions, visibility, vehicle types, and the timing of deployment of snowplows and salt spreaders.[764] For example, it was concluded that early deployment of winter maintenance operations can improve crash prevention and that delays between salting and snowplowing can result in more crashes. More research is required to better quantify the benefits of road salting.

Regarding the costs of road salting, WisDOT reported that in the winter of 2019/2020, the average cost of road salt purchased was $80 per ton and accounted for 35 percent of the total winter maintenance costs.[765] Based on this figure, the cost of labor and equipment for winter maintenance during the 2019/2020 winter season would have been approximately $150 per ton of road salt used. These figures are similar to what was reported by several Minnesota studies. [766,767] As discussed in previous sections, the costs of salt usage are not the only costs associated with road salting. Costs also include motor vehicle, infrastructure, and environmental damage caused by its usage. In 1976, an USEPA study estimated that the national cost of salt-related damages to vehicles and infrastructure was 15 times higher than the cost to purchase and apply road salt.[768] Applying this estimate to the WisDOT reported road salt costs yields $3,450 of damages per ton of road salt used. In a later 1992 study, $803 of vehicle and infrastructure damages per ton of road salt applied was estimated.[769] After adjusting for inflation, that damage estimate would be approximately $1,550 per ton of road salt used (2021 dollars). Based on these estimates, $1 spent on direct winter maintenance operation can cause between $7 and $15 of damages to motor vehicles and infrastructure.

Based on the studies mentioned above, the lower estimate of damages is approximately equal to the higher estimate of economic benefits of road salting.[770] In terms of accident economics, it can be roughly concluded that the costs of road salting may be equal to but is likely greater than the benefits of road salting. However, the estimated benefits of road salting were purely in terms of accident economics and do not factor in many indirect economic benefits [771], and the value of human life and safety. When those are accounted for, the benefits most likely outweigh the costs of road salting. Nevertheless, value can be gained from reducing the usage of road salt. The quantity and strategy of road salt applications can be optimized to provide roadway safety benefits while reducing damages to the natural and built environment. A further discussion on the state-of-the-art road salt usage, application strategies, and alternatives can be found in SEWRPC Technical Report No. 66, *State of the Art of Chloride Management* (in development).

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[764] *X. Qin, D.A. Noyce, C. Lee, and J.R. Kinar, "Snowstorm Event-Based Crash Analysis,"* Transportation Research Record*, 1948: 134-141, 2006.*

[765] *Wisconsin Department of Transportation, "Annual Winter Maintenance Report 2020/2021", 2021.*

[766] *C. Dindorf, C. Fortin, B. Asleson, and J. Erdmann, "The Real Cost of Salt Use for Winter Maintenance in the Twin Cities Metropolitan Area," Fortin Consulting, Inc. and Minnesota Pollution Control Agency, 2014.*

[767] *H. Stefan, E. Novotny, A. Sander, and O. Mohseni, "Study of Environmental Effects of De-icing Salt on Water Quality in the Twin Cities Metro Area, Minnesota," Minnesota Department of Transportation, Local Road Research Board, Report 2008-42, 2008.*

[768] *D.M. Murray and U.F. Ernst, 1976,* op. cit*.*

[769] *D.F. Vitaliano, "An Economic Assessment of the Social Costs of Highway Salting and the Efficiency of Substituting a New Deicing Material,"* Journal of Policy Analysis and Management*, 11(3): 397-418, 1992.*

[770] *It should be noted that these estimates are highly approximate and should be used with caution.*

[771] *Indirect economic impacts from a snowstorm can include the loss of wages, taxes, and sales due to the closure of businesses and roads. IHS Global Insights estimated the indirect economic impacts for a widespread snowstorm in Wisconsin can cost $150 million (see IHS Global Insights, "The Economic Costs of Disruption from a Snowstorm", The American Highway Users Alliance, 2010).*

IMPACTS OF CHLORIDES ON HUMANS AND HUMAN ACTIVITIES 5

Credit: Wikimedia Commons User Netha Hussain

5.1 INTRODUCTION

The use of chloride salts provides several benefits to humans and human activities. Application of deicing salt to roads prior to, during, and following winter weather events reduces the risk of traffic accidents associated with poor road conditions. Deicing salt use also reduces the risk of slip and fall accidents, preventing injuries to pedestrians. Ion exchange water softeners are recharged with a sodium chloride brine. The use of these softeners protects plumbing and appliances, lengthening their useful lives. Potassium chloride is also used as a fertilizer, increasing crop yields.

Despite these benefits, elevated concentrations of chloride salts in the environment can have adverse effects on human activities. High concentrations of chloride salts affect the suitability of water for human consumption both because of the effects of the salts on the taste of water and the direct and indirect effects of the salts on human health. Contamination with chloride salts can also reduce the suitability of soil and irrigation water for agricultural use. Mobilization of chloride salts into the atmosphere can contribute to particulate pollution in the air, which can affect human health. Finally, the use of chloride salts can affect other activities including recreation, cleaning of the interiors of buildings during the winter, and roadside aesthetics.

As noted in previous Chapters of this Report, concentrations of chloride salts, associated salinity and specific conductance have been increasing in surface waters, both in the Southeastern Wisconsin Region and much of the nation.[772] As discussed in previous Chapters of this Report, increases of chloride salts in the environment have the potential to impact and alter ecological systems and contribute to the deterioration of vehicles and transportation and water supply infrastructure.

[772] *See for example, Richard C. Lathrop, "Chloride and Sodium Trends in the Yahara Lakes,* Research Management Findings, *No.12, Wisconsin Department of Natural Resources, June 1998; S.R. Corsi, L.A. De Cicco, M.A. Lutz, and R.M. Hirsch, "River Chloride Trends in Snow-Affected Urban Watersheds: Increasing Concentrations Outpace Urban Growth Rate and Are Common Among All Seasons,"* Science of the Total Environment,*508:488-497, 2015; and J.A. Thornton, T.M. Slawski, and H. Lin, "Salinization: The Ultimate Threat to Temperate Lakes, with Particular Reference to Southeastern Wisconsin (USA),"* Chinese Journal of Oceanology and Limnology, *33:1-15, 2015.*

This Chapter presents the findings of a literature review of the impacts of chloride salts on human health and human activities. Health effects of elevated concentrations of chloride salts include direct effects on human cardiovascular and respiratory systems, as well as indirect effects that can occur through the promotion of the release of heavy metals by these salts. Health effects also include those related to the contributions of chloride salts to aerial particulates. The chapter also discusses the impact of chloride salts on agricultural systems and the potential effects of elevated concentrations of chloride salts on recreational opportunities and aesthetics.

5.2 BENEFITS OF CHLORIDE SALT USE TO HUMANS

The use of chloride salts provides several benefits to humans. These include improving traffic safety, improving the safety of pedestrians, reducing the infrastructure problems associated with hard water, and improving crop production. This section describes several benefits of chloride use.

Traffic Safety

Road and weather conditions during winter present challenges to motorists. Weather events, including heavy snow as the most severe condition, can reduce traffic volumes by up to 44 percent, reduce average speeds by up to 40 percent, reduce road capacity by up to 30 percent, and increase travel time delays by up to 50 percent.[773] Snow-, slush-, and ice-covered roads can produce hazardous driving conditions which can lead to accidents that cause deaths, injuries, and property damage. Snow, slush, and ice reduce friction between the pavement and vehicle tires, making safe operation of the vehicle more difficult. This hazard can be compounded by at least two issues. First, ice is not always visible to motorists, nor is it uniformly distributed on pavement. Second, snowstorms affect driver behavior leading to lower speeds and more variable speeds, which increases the risk of accidents occurring.[774]

In 2021, there were 24,234 traffic accidents reported on roads in Wisconsin that were covered by snow, slush, and/or ice.[775] These accidents represented about 19 percent of the traffic accidents that occurred in the State that year. In 45 of these accidents at least one person was killed, and in another 3,655 of these accidents at least one person was injured.

Winter weather and the presence of snow, slush, and ice on roads can increase the rates at which accidents occur. A comparison of crash rates in the State of Washington found that the frequency of traffic accidents in the presence of snow was about five times the frequency of accidents under clear conditions.[776] This study also found that about twelve times the number of accidents occurred in Washington during the month of January than occurred during the month of July.

The response to winter weather can affect the likelihood that accidents will occur. A study that investigated the impact of snowstorms on Wisconsin State Trunk Highways found that a large percentage of accidents that occur during a snowstorm happen during the initial stages of the storm.[777] The authors attributed this to the fact that winter maintenance activities have not begun during the early stages of a storm. This study also found that during later stages of a snowstorm, a greater percentage of accidents occurred on local roads than on State highways. They may reflect that these roads receive different levels of winter maintenance.

Some studies have attempted to evaluate the effects of applying chemical deicers to roads on accident rates during snowstorms. One such study documented accident rates before and after winter road maintenance

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[773] *U.S. Federal Highway Administration,* How Do Weather Events Impact Roads?, *2018.*

[774] *X. Qin, D.A. Noyce, C. Lee, and J.R. Kinar, "Snowstorm Event-Based Crash Analysis,"* Transportation Research Record, Journal of the Transportation Research Board*, 1,948(1):135-141, 2006.*

[775] *Wisconsin Department of Transportation, "2021 Crash Facts," www.content.dot.wi.gov/content/crashfacts/2021/index.html, accessed February 9, 2024.*

[776] *L.C. Goodwin,* Best Practices for Road Weather Management, *U.S. Federal Highway Administration Report No. FHWA-OP-03-081, 2003.*

[777] *Qin et al. 2006,* op. cit.

operations began during winter storm events over a four-year period in Germany.[778] This study examined over 4,700 accidents that occurred on about 400 miles of roads in rural and suburban areas. It analyzed hourly accident rates in the 12 hours before and after application of deicing salt began. During the 12-hour period prior to salt spreading, traffic accident rates ranged between about 2.8 and 16.7 accidents per motor vehicle miles traveled (MVMT), averaging about 9.6 accidents per MVMT over the period. In the 12 hours following salt application accident rates ranged between about 1.9 and 4.0 accidents per MVMT, averaging about 2.7 accidents per MVMT.

A second study used similar methods to examine the effectiveness of deicer application on reducing accidents on two-lane highways and freeways in nine counties in the States of Illinois, Minnesota, New York, and Wisconsin during the winter of 1990-1991.[779] On two-lane highways, this study compared the rates of accidents in the four hours before and after salt application began. It found that salt application reduced the rates of all accidents on two-lane roads during the four hours following salt application by about 87 percent. After deicing the accidents resulting in at least one injury and accidents with property damage were reduced by 88 percent and 85 percent, respectively. The study also found that salt application reduced the average cost of an accident by about 10 percent. This study also compared the rates of accidents on freeways in the two hours before and after salt application began. It found that salt application reduced the rates of all accidents on freeways during the two hours following salt application by about 78 percent. After deicing the freeway accidents resulting in at least one injury and accidents with property damage were reduced by 85 percent and 56 percent, respectively. The study also found that salt application reduced the average cost of a freeway accident by about 30 percent. The study cost-benefit analysis concluded that salt application on two-lane highways provides $6.50 of benefit for every $1.00 spent. Similarly, the study found that salt application on freeways provides $3.50 for every $1.00 spent. Note that an additional cost-benefit analysis of road salting is provided in Chapter 4 of this Report.

Subsequent research has criticized the before and after comparison methodology used in the studies described in the previous two paragraphs for not controlling for factors that could potentially confound the results.[780] A third study constructed a computer model based on a road surface condition index. This model controlled for factors such as weather, road geometry, and traffic. This study found that road salt application could reduce the number of accidents by between 20 and 85 percent, depending on the existing conditions when salt is applied and the degree of improvement in road conditions following salt application.

This study also conducted a before and after comparison similar to the comparisons made in the studies previously described.[781] This comparison was conducted using finer scale methods that allowed the authors to separate the effects of only salting on accident rates from those of salting combined with snow plowing. The comparisons also examined a wider range of highway types than in the previous studies. This study found that salting alone led to a 51 percent reduction in accident rates. Salting combined with snow plowing led to a 65 percent reduction in accident rates. The authors stated that these reduction magnitudes should be interpreted cautiously because this type of comparison lacks controls for factors such as visibility, traffic volume, traffic speed, and wind speed. While they were confident that winter road maintenance activities had reduced accident rates, they were less confident about the magnitude of the reductions.

In conclusion, the results of all of these studies indicate that that the use of deicing salts as part of winter road maintenance provides benefits to humans by reducing the number of traffic accidents and the fatalities, injuries, and property damage caused by such accidents. The magnitude of this benefit is difficult to determine, both because it is hard to separate the effects of salting from those of other winter road maintenance activities such as snow plowing and how numerous other factors such as type of road, traffic volume, traffic speed, and visibility affect accident rates.

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[778] *H. Hanke and C. Levin,* Influence of Winter Road Maintenance on Traffic Safety and Transport Efficiency, *Darmstadt Technical University, Darmstadt, Germany, 1988, in German described in D. Kuemmel and R. Hanbali,* Accident Analysis of Ice Control Operations*, Department of Civil, Construction, and Environmental Engineering, Marquette University, Milwaukee, Wisconsin, June 1, 1992.*

[779] *Kuemmel and Hanbali 1992,* op. cit.

[780] *L. Fu and T. Usman,* Safety Impacts of Using Deicing Salt*, Department of Civil and Environmental Engineering, University of Waterloo, Waterloo, Ontario, Canada, 2014.*

[781] Ibid.

Slip and Fall Prevention

The use of chloride-based deicers can help to prevent slip and fall accidents. Accumulation of snow and ice on surfaces like sidewalks, parking lots, steps, and ramps make walking difficult. This can lead to greater risk of slip and fall accidents that can result in injuries. A study of seasonal variations in fall-related hospital emergency department visits found that the number of such visits was higher during the winter than during other seasons.[782] Studies have also found that a higher risk of fall injuries occurs immediately after periods of snowfall and freezing rain.[783]

The presence of snow and/or ice is a major factor contributing to slip and fall accidents. A study examining fall accidents among 40 postal delivery workers in the United Kingdom found that about 40 percent of these accidents involved snow and another 30 percent involved ice.[784] A follow up to this study examined fall accident data among 1,734 postal delivery workers over a two-year period.[785] This study found that the most common event initiating a fall was a foot slipping, with about 46 percent of these slips occurring on ice. The study also found that slipping accidents tended to be clustered on single days where heavy snowfall or ice made conditions particularly hazardous. In addition, over 90 percent of the employees whose falls were investigated mentioned that snow or ice was one of the contributing factors.

Adults aged 65 years and older are particularly vulnerable to slip and fall injuries. In 2018 in the United States, fall-related injuries led to about three million hospital emergency department visits, over 950,000 hospital admissions, and about 32,000 deaths among older adults.[786] Not all of these fall-related injuries were caused by snow and ice conditions. Further examination of the data showed that about 72 percent of these injuries occurred indoors with the remaining 28 percent occurring outdoors.[787] This suggests that the presence of snow and ice was probably still a factor in a substantial number of falls among older adults.

Application of deicing chemicals can reduce the risk of slip and fall accidents by reducing ice buildup on surfaces. Proper application of deicing salts is discussed in an accompanying technical report.[788]

Water Softening

Hardness of water is caused by dissolved minerals, especially dissolved ions of calcium and magnesium. Groundwater in most of the Southeastern Wisconsin Region is either hard or very hard, with hardness of shallow groundwater in much of the Region being greater than 180 milligrams per liter as calcium carbonate.[789] This can lead to problems as much of the Region uses groundwater as a source of water supply.

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782 *R.S. Kakara, B.L. Moreland, Y.K. Haddad, I. Shakya, and G. Bergen, "Seasonal Variation in Fall-Related Emergency Department Visits by Location of Fall—United States, 2015,"* Journal of Safety Research*, 79:38-44, 2021.*

783 *A.N. Dey, P. Hicks, S. Benoit, and J.I. Tokars, "Automated Monitoring of Clusters of Falls Associated with Severe Winter Weather Using the BioSense System,"* Injury Prevention*, 16:403-407, 2010; K. Gevitz, R. Madera, C. Newbern, J. Lojo, and C.C. Johnson, "Risk of Fall-Related Injury Due to Adverse Weather Events, Philadelphia, Pennsylvania, 2006-2011,"* Public Health Report*, 132(1 Supplement): 53S-58S, 2017; J.F. Bobb, K.K. Ho, R.W. Yeh, L. Harrington, A. Zai, K.P. Liao, and F. Dominici, "Time-Course of Cause-Specific Hospital Admissions During Snowstorms: An Analysis of Electronic Medical Records from Major Hospitals in Boston, Massachusetts,"* American Journal of Epidemiology*, 185:283-294, 2017.*

784 *R.A. Haslam and T.A. Bentley, "Follow-Up Investigations of Slip, Trip, and Fall Accidents among Postal Delivery Workers,"* Safety Science*, 32:33-47, 1999.*

785 *T.A. Bentley and R.A. Haslam, "Slip, Trip, and Fall Accidents Occurring during the Delivery of Mail,"* Ergonomics*, 41:1,859-1,872, 1998; T.A. Bentley and R.A. Haslam, "Identification of Risk Factors and Countermeasures for Slip, Trip, and Fall Accidents During the Delivery of Mail,"* Applied Ergonomics*, 32:127-134, 2001.*

786 *B. Moreland, R. Kakara, and A. Henry, "Trends in Nonfatal Falls and Fall-Related Injuries among Adults Aged ≥ 65 Years—United States, 2012-2018,"* Morbidity and Mortality Weekly Report*, 69:875-881, 2020.*

787 *B.L. Moreland, R. Kakara, Y.K. Haddad, I. Shakya, and G. Bergen, "A Descriptive Analysis of Older Adult Falls that Resulted in Emergency Department Visits in the United States, 2015,"* American Journal of Lifestyle Medicine*, 15:590-597, 2020.*

788 *SEWRPC Technical Report No. 66,* State of the Art in Chloride Management*, in preparation.*

789 *SEWRPC Technical Report No. 37,* Groundwater Resources of Southeastern Wisconsin*, June 2002.*

Several problems are associated with the use of hard water. Hard water can lead to formation of lime scales that have damaging effects on plumbing and appliances.[790] Scale can clog pipes, reducing water flow. An example of this is shown in Figure 5.1. Scale can also reduce the efficiency of boilers and water heaters, sometimes by as much as 50 percent.[791] Appliances such as washing machines and dishwashers can also be damaged by scale. Mineral deposits from hard water can damage chrome fixtures. These impacts from hard water can increase the costs of operating water heaters and other appliances and can ultimately shorten their useful lives, leading to early replacement and the associated costs.

Figure: 5.1
Scale Build-up in a Water Pipe

Source: Wikimedia User Alexander Yurievich Lebedev

The calcium and magnesium ions in hard water also reduce the effectiveness of soaps, detergents, and other cleaning agents. This can require the use of more detergent to achieve clean conditions as compared to what could be achieved using soft water. For example, one study of laundry detergents found that powdered detergents performed significantly worse in hard water than in soft water.[792] Bringing clothing washed in hard water to the same level of cleanliness as was achieved in soft water required the use of 10 to 30 percent more detergent, which increases the cost of cleaning. Cleaning using hard water can also lead to problems such as the formation of films on dishes, glasses, and sinks, and dingy looking clothing.

In homes and businesses, hard water is often treated by point of entry ion exchange water softeners. These softeners capture calcium and magnesium ions on an ion exchange resin and release sodium to the water. The resin is periodically recharged by passing a sodium chloride brine through the softener which results in a waste stream containing chloride ions. Proper calibration and use of water softeners and potential alternatives to ion exchange methods for softening are discussed in an accompanying technical report.[793]

Crop Growth

Chloride salts are used as fertilizers for plant growth. As discussed in Chapter 3 of this report, chloride is an essential micronutrient for plants. Chloride deficiency can occur when soils contain very low levels of chlorides. Soils commonly contain about 20,000 parts per million (ppm) potassium. Most of this is unavailable to plants because it is bound in the crystalline structure of minerals in the soil. Weathering of these minerals can release potassium, but this occurs too slowly to supply the needs of crops.[794] As a result, potassium fertilizers are often applied to agricultural fields. Potassium chloride, also known as muriate of potash, is the most commonly used potassium fertilizer.[795] Alternatives to the use of potassium chloride are discussed in an accompanying technical report. [796] The use of potassium chloride fertilizer adds about 0.9 pound of chloride to soil for every pound of potassium added.[797]

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[790] *A.J. Heidekamp and A.T. Lemley,* Water Bulletin: Hard Water, *Cornell University Cooperative Extension, April 2005.*

[791] *U.S. Department of Energy, "Reasons Every Home Should Have a Water Softener," www.energy.gov/energysaver/articles/reasons-every-home-should-have-water-softener. September 13, 2023, accessed February 6, 2024.*

[792] *B.A. Cameron, "Detergent Considerations for Consumers: How Much Extra Detergent is Required?"* Journal of Extension*, 49(4):4RIB6, 2011.*

[793] *SEWRPC Technical Report No. 66,* op. cit.

[794] *E.E. Schulte and K.A. Kelling,* Understanding Plant Nutrients: Soil and Applied Potassium*, University of Wisconsin Extension Fact Sheet A2521, no date.*

[795] *E.E. Schulte, L.M. Walsh, K.A. Kelling, L.G. Bundy, W.L. Bland, R.P. Wolkowski, J.B. Peters, and S.J. Sturgul,* Management of Wisconsin Soils (fifth edition)*, University of Wisconsin-Extension, 2005.*

[796] *SEWRPC Technical Report No. 66,* op. cit.

[797] *E.E. Schulte,* Understanding Plant Nutrients: Soil and Applied Chlorine, *University of Wisconsin-Extension Fact Sheet A3556, 1999.*

The symptoms of chloride deficiency vary among different plants. In wheat this deficiency appears as random spots of yellowing on leaves.[798] Crops experiencing chloride deficiency have been reported in the States of Kansas and Montana[799] but not in Wisconsin.[800]

Potassium chloride is commonly applied to agricultural lands because potassium is an essential macronutrient for plants. Shortages of potassium in soils can markedly reduce crop yields.[801] Shortages of potassium can also reduce crop quality. For example, insufficient potassium in soils reduce the percentage of legumes occurring in pasture plants.[802]

Potassium has several roles in plant nutrition.[803] It is important in the movement of water, nutrients, and carbohydrates through plants. In corn, potassium helps prevent breakage of corn stalks below the ear.[804] The overall effects of potassium on plant growth include:

- Increased root growth
- Improved drought resistance
- Reduced water loss and wilting
- Increased plant protein contents
- Retardation of some crop diseases

The symptoms of potassium deficiency vary among species of plants.[805] On field crops, this deficiency appears as yellowing or scorching on the margins of older leaves. On other crops, it may appear as whitish-gray spots on the outer margins of recently matured and older leaves. As the deficiency increases, leaves may turn completely yellow or drop off the plant. Examples of plants suffering from potassium deficiency are shown in Figure 5.2.

Plant requirements for potassium vary among species.[806] Corn, soybeans, and small grains have relatively low potassium requirements. Alfalfa, beans, clovers, wheat, and some other field crops have intermediate needs. Tomatoes, peppers, and leafy greens have relatively high needs. Potatoes have very high needs. Potassium is removed from agricultural fields in the harvest portions of crops. When optimum amounts of potassium for the intended crop and yield are present in the soil, only enough potassium fertilizer should be applied to replace the amount of potassium removed through harvesting.[807]

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[798] *R.E. Lamond, and D.F. Leikam,* Chloride in Kansas: Plant, Soil, and Fertilizer Considerations*, Kansas State University, December 2002.*

[799] Ibid.

[800] *Schulte 1999,* op. cit.

[801] *K.A. Kelling, L.G. Bundy, S.M. Combs, and J.B. Peters,* Optimum Soil Test Levels, *University of Wisconsin-Extension R-11-99-2M-100, 1999.*

[802] *K. Barnett, T. Cadwallader, R. Halopka, M. Bendixen, and N. Schneider, "Potassium Fertilizer Management of Pastures,"* Graziers Notebook, *5(2):1-6, 2011.*

[803] *University of Minnesota Extension, "Potassium for Crop Production," extension.umn.edu/phosphorus-and-potassium/potassium-crop-production, accessed February 6, 2024.*

[804] *Kelling et al. 1999,* op. cit.

[805] *Schulte and Kelling nd,* op.cit..

[806] *C.A.M. Laboski and J.B. Peters,* Nutrient Allocation Guidelines for Field, Vegetable, and Fruit Crops in Wisconsin, *University of Wisconsin-Extension, 2012.*

[807] Ibid.

Figure 5.2
Symptoms of Potassium Deficiency in Crop Plants

Source: Wikimedia Commons User Alan D. Manson

5.3 IMPACTS OF CHLORIDE SALTS ON HUMAN HEALTH

Elevated concentrations of chlorides can affect human health. Some health effects are related to the consumption of drinking water with elevated concentrations of chloride salts. While drinking water is not the primary source of these salts, it can contribute to the salt dose people receive. Other health effects are related to direct contact with chloride salts or the presence of particles or aerosols containing chloride salts in the atmosphere. Some health impacts are directly caused by chloride salts, especially the cation sodium. Other health impacts occur indirectly through chloride salts participating in chemical reactions that release other substances that can affect human health. This section describes health impacts caused by chloride salts.

Effects on Blood Pressure and Cardiovascular Health

Hypertension or high blood pressure is defined as systolic blood pressure greater than 130 millimeters of mercury (mm Hg)[808] or a diastolic blood pressure greater than 80 mm Hg.[809] About 116 million adults in the United States either have or are taking medication to treat hypertension.[810]

Role of Salt and Sodium in Hypertension

The role of dietary consumption of salt as a cause of hypertension has been recognized for over a century.[811] The incidence of hypertension in members of cultures that have low salt intake is low.[812] In addition, blood

[808] *Acronyms and abbreviations used in this report are defined in Appendix A.*

[809] *Systolic blood pressure is the maximum blood pressure during a heartbeat. Diastolic blood pressure is the minimum blood pressure between two heartbeats.*

[810] *U.S. Centers for Disease Control and Prevention,* Hypertension Cascade: Hypertension Prevalence, Treatment and Control Estimates Among U.S. Adults 18 Years and Older Applying the Criteria from the American College of Cardiology and American Heart Association's 2017 Hypertension Guideline—NHANES 2015-2018, *U.S. Department of Health and Human Services, 2021.*

[811] *For example: L. Ambard and E. Beaujard, "Causes de l'Hypertension Arterielle,"* Archives of General Medicine*, 1:520, 1904, cited in: E.M. Freis, "Salt, Volume and the Prevention of Hypertension,* Circulation*, 53:589-595, 1976.*

[812] *B. Kaminer and W.P.W. Lutz, "Blood Pressure in Bushmen of the Kalahari," Circulation, 22:289-295, 1960; C.J. Burns-Cox and J.D. McLean, "Splenomegaly and Blood Pressure in an Orang Asli Community in West Malaysia,"* American Heart Journal*, 80:718-719, 1970.*

pressure does not generally rise as members of these cultures age.[813] This is unlike the pattern seen in cultures in which higher dietary intake of salt is the norm. Also, the incidence of hypertension and blood pressure rising with age in low dietary salt cultures increases as salt use increases, especially in conjunction with migration.[814] Finally, epidemiological and other data have shown that higher salt diets can lead to increased blood pressure.[815]

Evidence Relating Sodium Intake to Hypertension

The effect of salt ingestion on blood pressure has been linked to the intake of sodium. At least three lines of evidence support the idea that long-term ingestion of high levels of sodium leads to an increase in blood pressure. First, epidemiological comparisons of neighboring communities show that a greater incidence of high blood pressure is associated with higher concentrations of sodium in drinking water. For example, a study of two communities with drinking water concentrations of sodium of 8 mg/l and 108 mg/l found a significantly higher incidence of high blood pressure in the community with the higher sodium level after controlling for 18 other factors.[816]

Second, experimental reductions of sodium intake have been shown to lead to lower blood pressure. For example, a meta-analysis of 31 studies in which sodium intake was reduced for more than four weeks found a median reduction in dietary sodium of about 1,810 milligrams per day (mg per day) led to reductions of 2.03 mm Hg of systolic blood pressure and 0.99 mm Hg diastolic blood pressure.[817] This sodium reduction is equivalent to a salt reduction of 4,600 mg per day. This study also found that the greater the reduction in salt intake, the greater reduction in blood pressure. The study concluded that in people with elevated blood pressure, a reduction of sodium intake of 2,360 mg per day or a reduction of about 6,000 mg salt per day would lead to reductions of 7.2 mm Hg systolic blood pressure and 3.8 mm Hg diastolic blood pressure. Smaller reductions were predicted to occur in people with normal blood pressure. In people with elevated blood pressure, reductions of this magnitude would be expected to reduce deaths from stroke and ischemic heart disease by 14 percent and 9 percent, respectively.[818] The authors of the meta-analysis noted that since the median duration of the studies examined was five weeks, longer-term reductions in sodium intake could potentially lead to greater reductions in blood pressure than found in their analysis.

Third, studies have found relationships between increases in salinity in drinking water and increases in blood pressure. For instance, a study in Bangladesh found that an increase of 1,000 mg/l in drinking water salinity led to a 2.2 mm Hg rise in systolic blood pressure.[819] Studies have also documented seasonal increases in hypertension, heart attack, and stroke during winter months that might be related to elevated levels of sodium in drinking water.[820]

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[813] *F.W. Lowenstein, "Blood Pressure in Relation to Age and Sex in the Tropics and Subtropics: A Review of the Literature and an Investigation in Two Tribes of Brazil Indians,"* The Lancet*, 277:389-392, 1961.*

[814] *R. Cruz-Coke, R. Etcheverry, and R. Nagel, "Influence of Migration on Blood Pressure of Easter Islanders,"* The Lancet*, 283:697-699, 1964.*

[815] *Freis 1976,* op. cit.

[816] *E.J. Calabrese and R.W. Tuthill, "Sources of Elevated Sodium Levels in Drinking Water and Recommendations for Reduction,"* Journal of Environmental Health*, 41:151-155, 1978.*

[817] *F.J. He and G.A. MacGregor, "Effect of Longer-Term Modest Salt Reduction on Blood Pressure (Review),"* The Cochrane Library*, Issue 3, 2006.*

[818] *S. MacMahon, R. Petro, J. Cutler, J. Collins, et al., "Blood Pressure, Stroke, and Coronary Heart Disease. Part I, Prolonged Differences in Blood Pressure: Prospective Observational Studies Corrected for Regression Dilution Bias,"* The Lancet*, 335:765-774, 1990.*

[819] *M.R.R. Talukder, S. Rutherford, C. Huang, D. Phung, et al., "The Effect of Drinking Water Salinity on Blood Pressure in Young Adults of Coastal Bangladesh,"* Environmental Pollution*, 214:248-254, 2016.*

[820] *T. Takenaka, E. Kojima, K. Sueyoshi, T. Sato, et al., "Seasonal Variations of Daily Changes in Blood Pressure among Hypertensive Patients with End-Stage Renal Diseases,"* Clinical and Experimental Hypertension*, 32:221-233, 2010; A. Fares, "Winter Cardiovascular Diseases Phenomenon,"* North American Journal of Medical Sciences*, 5:266, 2013.*

Excess sodium affects blood pressure through its impact on extracellular fluids.[821] As sodium accumulates in tissue, the body retains water to dilute the sodium. This increases the amount of fluid surrounding cells and the volume of the blood. This fluid increase can lead to stiffening and structural narrowing of arteries and arterioles.[822] This change in blood vessels causes increased resistance to blood flow which results in higher blood pressure.

Human Sodium Requirements

Sodium is a required nutrient for humans for numerous biological processes. It has an important role in the transmission of nerve impulses. When a nerve cell transmits an impulse, sodium ions flow into the cell from the extracellular fluid.[823] Sodium plays a similar role in the initiation of contraction and relaxation of muscles. Finally, sodium ions are necessary for maintaining the proper balance of water and minerals in bodily fluids.[824]

Several agencies have recommended levels of human sodium intake based on different physiological thresholds and medical conditions. The minimum amount of sodium that adults need to maintain physiological functions is about 500 mg per day.[825] The U.S. Institute of Medicine of the National Academies of Sciences, Medicine, and Engineering has issued a guideline for the adequate sodium intake for adults. This guideline for sodium of 1,200 to 1,500 mg per day represents the lowest level at which nutritional deficiencies were not observed.[826] This institute has also established a tolerable upper limit for sodium intake for adults of 2,300 mg per day.[827] The Blood and Lung Institute of the National Institutes of Health recommends that adults on a low sodium diet ingest no more than 1,500 mg of sodium per day.[828] By way of comparison, the average sodium intake of American adults is about 3,400 mg per day.

Although intake through food is the main source of sodium to humans, higher levels of sodium in drinking water can contribute to health problems. The U.S. Environmental Protection Agency (USEPA) has issued a health advisory that recommends that concentrations of sodium in drinking water not exceed 20 mg/l.[829] This advisory was based on the risks posed by sodium to individuals with salt restricted diets. Water utilities are required to report exceedances of this 20 mg/l level to public health officials so that physicians can advise high-risk patients.

Consequences of Hypertension

Hypertension is an important precursor to other medical conditions. In 2021, hypertension was a primary or contributing cause of over 691,000 deaths in the United States.[830] High blood pressure is a potential cause of several other heart and vascular diseases. It is a major risk factor for coronary heart disease which involves the reduction of blood flow to the heart due to the buildup of atherosclerotic plaque in arteries of

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[821] *Harvard T.H. Chan School of Public Health,* Salt and Sodium*, www.hsph.harvard.edu/nutritionsource/salt-and-sodium/, accessed April 28, 2023.*

[822] *B. Folkow, "Physiological Aspects of Primary Hypertension,"* Physiological Reviews*, 62:347-504, 1982.*

[823] *M.W. Barnett and P.M. Larkman, "The Action Potential,"* Practical Neurology*, 7:192-197, 2007.*

[824] *Harvard T.H. Chan School of Public Health,* op. cit.

[825] *National Research Council Subcommittee on the Tenth Edition of the Recommended Dietary Allowances,* Recommended Dietary Allowances*, National Academies Press, Washington, D.C., 1989.*

[826] *U.S. Institute of Medicine,* Dietary Reference Intakes for Water, Potassium, Sodium, Chloride, and Sulfate, *National Academies Press, Washington, D.C., 2005.*

[827] Ibid.

[828] *National Institutes of Health,* Your Guide to Lowering Your Blood Pressure with DASH (No. 6), *2006.*

[829] *U.S. Environmental Protection Agency,* Drinking Water Advisory: Consumer Acceptability and Health Effects Analysis on Sodium*, EPA 822-R-03-006, 2003.*

[830] *National Center for Health Statistics,* Multiple Cause of Death 2018-2021 on CDC WONDER Database*, Accessed May 30, 2023.*

the heart.[831] About half of all heart attacks can be attributed to high blood pressure.[832] Hypertension is also a major factor leading to strokes,[833] accounting for about two-thirds of all strokes.[834] High blood pressure is a risk factor for atrial fibrillation which consists of an abnormal heart rhythm consisting of rapid, irregular beating of the atrial chambers of the heart.[835] Congestive heart failure and aortic aneurysms can also be

attributed to high blood pressure. Hypertension is also a major risk factor for other medical conditions including vision loss, chronic kidney disease, and dementia.[836]

Effects on Air Quality

Air pollution presents a major health risk that contributes to several acute and chronic medical conditions including respiratory infections and diseases, heart disease, and cancer.[837] While several pollutants contribute to the health impacts of polluted air, respirable particulate matter, especially particulate matter with an aerodynamic diameter of 2.5 micrometers or smaller ($PM_{2.5}$), has a greater impact on human health outcomes than other ambient air pollutants.[838] Prolonged exposure to $PM_{2.5}$ has been associated with several health conditions. It is considered a cause of asthma and respiratory inflammation and can promote development of cancers, including lung cancer.[839] Reductions in ambient concentrations of $PM_{2.5}$ have been associated with longer life expectancies; however, the benefits of such reductions are generally greater in urban areas than in rural areas.[840] The authors of a study showing this suggested three possible explanations for this difference.[841] First, the chemical composition of $PM_{2.5}$ differs between urban and rural areas.[842] These differences may cause $PM_{2.5}$ to have larger health impacts in urban areas. Because the health impacts of $PM_{2.5}$ are greater in urban areas, reductions of $PM_{2.5}$ would lead to greater improvements in life span in those areas than in rural areas. Second, mortality rates are higher in rural areas than in urban areas. Several factors have been suggested to contribute to this geographical difference in death rates including physician shortages in rural areas, the relative lack of health insurance in rural areas, and the greater prevalence of poverty in rural areas.[843] Third, the geographical difference in death rate could potentially be an artifact

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[831] *S. Lewington, R. Clarke, Qizilbash, R. Peto, and R. Collins, "Age-Specific Relevance of Usual Blood Pressure to Vascular Mortality: A Meta-Analysis of Individual Data for One Million Adults in 61 Prospective Studies,"* The Lancet*, 360:1,903-1,913, 2002.*

[832] *F.J. He and G.A. MacGregor, "A Comprehensive Review on Salt and Health and Current Experience of Worldwide Salt Reduction Programs,"* Journal of Human Hypertension*, 23:363-384, 2009.*

[833] *M.A. Weber and D.T. Lackland, "Global Burden of Cardiovascular Disease and Stroke: Hypertension and the Core,"* Canadian Journal of Cardiology*, 31:569-571, 2015.*

[834] *He and MacGregor 2009,* op. cit.

[835] *D.H. Lau, S. Nattel, J.M. Kalman, and P. Sanders, "Modifiable Risk Factors and Atrial Fibrillation,"* Circulation*, 136:583-596, 2017.*

[836] *D.T. Lackland and M.A. Weber, "Global Burden of Cardiovascular Disease and Stroke: Hypertension at the Core,"* Canadian Journal of Cardiology*, 31:569-571, 2015; I. Hernandorena, E. Duron, J.S. Vidal, and O. Hanon, "Treatment Options and Considerations for Hypertensive Patients to Prevent Dementia,"* Expert Opinion on Pharmacotherapy*, 18:989-1,000, 2017.*

[837] *W.S. Beckett, "Current Concepts: Occupational Respiratory Diseases,"* New England Journal of Medicine*, 342:406-413, 2000; S. Karnae and K. John, "Source Apportionment of Fine Particulate Matter Measured in an Industrialized Coastal Urban Area of South Texas,"* Atmospheric Environment*, 45:3,769-3,776, 2011.*

[838] *D.W. Dockery et al., "An Association Between Air Pollution and Mortality in Six United States Cities,"* New England Journal of Medicine*, 329:1,753-1,759, 1993.*

[839] *See Y.-F. Xing, Y.-H. Xu, M.-H Shi, and Y.-X. Lian, "The Impact of PM2.5 on the Human Respiratory System,"* Journal of Thoracic Diseases*, 8:E69-E74, 2016 and the references therein.*

[840] *A.W. Correia et al., "Effect of Air Pollution Control on Life Expectancy in the United States: An Analysis of 545 U.S. Counties for the Period from 2000 to 2007,"* Epidemiology*, 24:23-31, 2013.*

[841] Ibid.

[842] *See, for example, Louie, P.K. et al., "$PM_{2.5}$ Chemical Composition in Hong Kong: Urban and Rural Variations,"* Science of the Total Environment*, 338:267-281, 2005.*

[843] *G. Gong et al., "Higher US Rural Mortality Rates Linked to Socioeconomic Status, Physician Shortages, and Lack of Health Insurance,"* Rural Health*, 38:201900722, 2019.*

resulting from misclassification of the exposure to $PM_{2.5}$ during data analysis. Since urban areas are more densely populated than rural areas, it is more likely that two persons in the same urban area would be exposed to the same levels of $PM_{2.5}$. Because of this, misclassification of exposure may be more likely in rural areas than urban areas. The USEPA has set a primary ambient air quality standard for $PM_{2.5}$ of 12 micrograms per cubic meter (μg/m^3) on an average annual basis.

Studies examining the sources and chemical composition of $PM_{2.5}$ have found that deicing salts constitute a measurable portion of ambient concentrations of these fine particulates. One study that monitored air quality over the Lake Champlain basin in Vermont found that road salt comprised about 4.6 percent of the ambient $PM_{2.5}$.[844] Other constituents of $PM_{2.5}$ included nitrates, wood smoke, soil, oil combustion products, automobile exhaust, sulfate-rich aerosols, and emissions from metal working. A second study investigated the composition and sources of $PM_{2.5}$ at rural and urban locations in Iowa between April 2009 and December 2012.[845] Concentrations of $PM_{2.5}$ tended to be higher and more variable at rural sites. Overall deicing salt represented about two to six percent of ambient $PM_{2.5}$, with it constituting two to three percent of $PM_{2.5}$ at urban sites and four to six percent of $PM_{2.5}$ at rural sites. The highest contributions of deicing salt to $PM_{2.5}$ were observed during winter months when deicing occurs. The percentages of $PM_{2.5}$ consisting of deicing salt in these two studies are consistent with those found in a third study which examined air quality in Detroit, Michigan.[846] This study found that deicing salt represented about five to eight percent of $PM_{2.5}$.

$PM_{2.5}$ is thought to be responsible for about 15 percent of lung cancer deaths.[847] Based on the fraction of $PM_{2.5}$ consisting of road salt, road salt applications may be associated with about one percent of all lung cancer deaths due to $PM_{2.5}$ levels in the United States.[848] Given that about 127,000 people die from lung cancer each year in the United States,[849] this suggests that road salt applications could be associated with about 190 deaths from lung cancer per year nationally.

Release of Heavy Metals from Water Sources and Drinking Water Infrastructure

Elevated concentrations of chloride salts can lead to the mobilization of heavy metals and metalloids from rock, sediment, and drinking water infrastructure into surface, groundwater, and potable water supplies. The mechanisms through which the release of metals occurs are discussed in Chapters 2 and 4 of this Report. When these metals and metalloids are released into water used for human consumption, they pose risks to human health through toxicity and other effects.

There are health concerns regarding approximately 23 different heavy metals. The most common of these substances include arsenic, cadmium, chromium, lead, and mercury. Other heavy metals of concern include copper, nickel, radium, silver, and zinc. While each of these metals can produce different health effects, general effects include reduced energy levels and damage to the functioning of the brain, nervous system, liver, lungs, blood, and other organs.[850] Long-term exposure to some of these metals can lead to progressive degenerative processes that mimic conditions such as Parkinson's disease, Alzheimer disease, and muscular dystrophy. Some heavy metals are also carcinogenic.

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[844] *N. Gao et al., "Sources of Fine Particulate Species in Ambient Air Over Lake Champlain Basin, VT,"* Journal of the Air and Waste Management Association*, 56:1,607-1,620, 2006.*

[845] *S. Kundu and E.A. Stone, "Composition and Sources of Fine Particulate Matter Across Urban and Rural Sites in the Midwestern United States,"* Environmental Science: Processes and Impacts*, 16:1,360-1,374, 2014.*

[846] *A.E. Gildenmeister, P.K. Hopke, and E. Kim, "Sources of Fine Urban Particulate Matter in Detroit, MI,"* Chemosphere*, 69:1,064-1,074, 2007.*

[847] *International Agency for Research of Cancer (IARC),* Outdoor Air Pollution: IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Volume 109, Lyon, France, 2013.*

[848] *M.H. Nazari et al., "Toxicological Impacts of Roadway Deicers on Aquatic Resources and Human Health: A Review,"* Water Environment Research*, doi: 10.1002/wer.1581, 2021.*

[849] *American Cancer Society,* Cancer Facts and Figures 2023*, American Cancer Society, Atlanta, Georgia, 2023.*

[850] *M. Jaishankar et al., "Toxicity, Mechanism and Health Effects of Some Heavy Metals,"* Interdisciplinary Toxicology,*" 7:60-72, 2014.*

Some heavy metals in drinking water can assume more than one chemical form, with some chemical forms being more toxic than others. Chromium, for example, can form two different ions, chromium (III) which has a positive charge of 3 and chromium (VI) which has a positive charge of 6. While both forms can produce adverse effects on the respiratory tract, chromium (VI) is much more toxic than chromium (III) and produces a wider range of adverse effects in humans.[851] This difference in toxicity between the two forms of chromium occurs with both acute and chronic exposures.

Some heavy metals are essential nutrients for humans. Trace amounts are required for certain biological processes. For example, humans require small amounts of zinc for the functioning of certain enzymes. Similarly, small amounts of copper are needed as a cofactor for the functioning of cytochrome oxidase C, a membrane protein that is important in cellular respiration. While humans and other organisms need small amounts of these elements, exposure to greater amounts can produce adverse effects.

Release of Heavy Metals into Source Water

Elevated concentrations of chloride salts can lead to heavy metal contamination of drinking water supply sources. For instance, sodium chloride or calcium chloride in deicing salts can mobilize mercury ions from sediment into water. One study found that such mobilization increased the amount of mercury ions in water by two to five orders of magnitude.[852] This effect increased as the concentration of chloride salts in the water and/or the concentration of mercury in sediment increased. At least two mechanisms contributed to the mobilization of mercury from the sediment. First, sodium and calcium ions from deicing salts compete with mercury ions for exchange sites on clay and humus particles. Second, chloride ions can form strong chemical complexes with mercury ions, making them more soluble in water. The mechanisms leading to mobilization of metals from soil and sediment are discussed in Chapter 2 of this Report.

Release of Metals from Drinking Water Infrastructure and Plumbing

Elevated levels of chloride in drinking water can lead to dezincification and galvanic corrosion of plumbing resulting in the leaching of metals from pipes and plumbing fixtures.[853] The mechanisms causing these processes were discussed in Chapter 4 of this Report. Another metal that can be released from plumbing is lead. In buildings with lead service lines or plumbing fixtures, such corrosion can lead to the release of lead into the drinking water. This was likely a factor in the lead contamination of drinking water in Flint, Michigan, as chloride concentrations in the City's drinking water increased from 11 mg/l to 94 mg/l following the switch of their water source to the Flint River. Similarly, a study in New York that examined deicing salt contamination in private wells found that about 24 percent of the homes studied had detectable lead levels in their drinking water after one minute of flushing.[854] The concentration of lead in the water was highly correlated with the concentrations of zinc and copper, suggesting that the source of the lead was corrosion of brass plumbing fixtures and fittings.

Service lines that transport drinking water from utility mains into buildings can be a source of lead. Historically, these pipes were often made from lead or galvanized iron which can also leach lead as it corrodes. In Wisconsin, responsibility for the service line is shared between the property owner and the municipal utility. Typically, the property owner is responsible for the portion of the service line that extends from the curb stop, where there is a control valve, into the building. The utility is responsible for the portion of the service line that extends from the water main to the curb stop. There are a substantial number of water service lines in the Southeastern Wisconsin Region that are made of lead or galvanized iron or that may contain lead. Table 5.1 shows the number of these lead-containing service lines in the Region at the end of 2022 as reported by the utilities in their annual reports to the Wisconsin Public Service Commission. As of 2022, there were more than 115,000 portions of service lines owned by utilities and more than 119,000 portions of service lines owned by property owners that were known to contain or suspected of containing lead or galvanized iron. This represents about

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[851] *Agency for Toxic Substances and Disease Registry,* Toxicological Profile for Chromium*, U.S. Public Health Service, 1998.*

[852] *G. Feick, R.A. Horne, and D. Yeaple, "Release of Mercury from Contaminated Freshwater Sediment by the Runoff of Road Deicing Salt,"* Science*, 175:1,142-1,143, 1972.*

[853] *K.J. Pieper et al., "Impact of Road Salt on Drinking Water Quality and Infrastructure Corrosion in Private Wells,"* Environmental Science and Technology*, 52:14,078-14,087, 2018.*

[854] Ibid.

24 percent of portions of service lines owned by utilities and 27 percent of service lines owned by property owners in the Southeastern Wisconsin Region.[855] Out of 70 water utilities in the Region, 32 reported the presence of service lines known to contain or suspected of containing lead. The highest numbers were reported by the utilities serving the Cities of Kenosha, Milwaukee, Racine, Wauwatosa, and West Allis and the Villages of Shorewood and Whitefish Bay.

Table 5.1
Water Service Lines Containing Lead or Galvanized Iron in Areas Served by Water Utilities in Southeastern Wisconsin: 2022

Water Service Line Material	Utility-Owned Service Lines	Customer-Owned Service Lines
Lead	112,629	108,498
Galvanized Iron	737	4,195
Unknown—May Contain Lead	2,276	6,366
Total	115,642	119,059

Source: Wisconsin Public Service Commission and SEWRPC

Exposure to lead can cause several adverse health effects. The most sensitive tissues are the nervous system, blood and cardiovascular system, and the kidneys. Developing nervous systems in children are especially susceptible to lead toxicity because exposure to lead during development can interfere with the formation, maintenance, and regulation of connections between nerve cells in the brain.

Relatively low levels of lead exposure can affect neurobehavioral development in children. This can result in cognitive deficits that may also be associated with distractibility, inability to inhibit inappropriate responses, and preservation of behaviors that are no longer appropriate. Somewhat higher levels of exposure can cause anemia due to the inhibitory effect of lead on the synthesis of heme, a component of hemoglobin, and shortening of the lifespan of red blood cells. These levels of lead exposure can also result in peripheral nerve dysfunction, resulting in weakness and loss of coordination in wrists, hands, feet, and ankles. Even higher levels of lead exposure can cause colic, kidney damage, muscle weakness, brain damage, paralysis, and death.

Prior to 2021, a lead blood concentration of 5 micrograms per deciliter (µg/dl) or more was considered indicative of lead poisoning. Based on data from local health departments, the Wisconsin Department of Health Services reported that from 2016 through 2020, an annual average of 2,600 children under six years of age out of an annual average of 42,702 tested in the seven-county Southeastern Wisconsin Region were found to have blood stream lead concentrations greater than 5 µg/dl. It should be noted that an unusually low number of children were tested in 2020, probably due to the Covid-19 pandemic. In addition, in late 2021, the U.S. Centers for Disease Control and Prevention lowered their reference level for identifying children with high blood levels of lead from 5 µg/dl to 3.5 µg/dl.[856] Thus, the average for 2016 through 2020 may underestimate the incidence of children suffering from lead poisoning in the Southeastern Wisconsin Region. More information on lead in drinking water can be found in a white paper issued by Commission staff.[857]

Other Health Effects

Intake of dietary sodium and salt have been linked to at least two other health conditions. Sodium intake may be a factor affecting the severity of osteoporosis. Increases in 24-hour urinary excretion of sodium, a surrogate for sodium intake, have been shown to indicate increases in the amount of calcium lost in urine and to the loss of hip bone density in post-menopausal women.[858] In addition, sodium intake greater than 4,600 mg per day was associated with the progression of chronic kidney disease.[859]

A study conducted in British Columbia noted that chloride-based deicing products can be irritating to skin and eyes on contact, depending on the duration, concentration, and frequency of exposure and individual

[855] *As of 2023. many utilities in the Region were still conducting inventories of service lines.*

[856] *As of June 7, 2023, Wisconsin Statute 254.11(9) defines the blood level indicating lead poisoning as 5 µg/dl.*

[857] *SEWRPC Staff Memorandum,* Lead in Drinking Water in Southeastern Wisconsin*, April 19, 2019.*

[858] *A. Devine, R.A. Criddle, I.M. Dick, D.A. Kerr et al.," A Longitudinal Study of the Effect of Sodium and Calcium Intakes on Regional Bone Density in Postmenopausal Women,"* American Journal of Clinical Nutrition*, 62:740-745, 1995.*

[859] *A. Smyth, M.J. O'Donnell, S. Yusuf, C.M. Clase, et al, "Sodium Intake and Renal Outcomes: A Systematic Review,"* American Journal of Hypertension*, 10: 1,277-1,284, 2014.*

sensitivities to the chemicals.[860] Calcium chloride was irritating to skin and eyes on contact. It can also produce toxic effects if inhaled. By contrast, sodium chloride and magnesium chloride were slight eye irritants. It should be noted that some non-chloride-based deicers, such as calcium magnesium acetate, were also found to be irritating to skin and eyes.

Contamination of groundwater by sodium chloride can lead to mobilization of radium into groundwater. This can lead to increased flux of radon gas and the accumulation of radon in buildings, leading to greater radon exposure to occupants.[861] The mechanisms through which radon exposure happens are discussed in Chapter 2 of this Report. Exposure to radon has been shown to cause lung cancer.[862] Radon exposure is the leading cause of death from lung cancer in nonsmokers. The USEPA estimates that radon is responsible for about 21,000 lung cancer deaths per year.[863] The lifetime risk in developing lung cancer from exposure to 4.0 picocuries of radon per liter air (pCi per l) is estimated as seven in 1,000 for nonsmokers and 62 in 1,000 for current smokers. Data from indoor air tests conducted between 1995 and 2016 indicate that this concentration often occurs in buildings in the Southeastern Wisconsin Region.[864] Across the Region, about 55 percent of over 32,000 tests reported concentrations of radon in buildings equal to or above this level. The percentage of radon tests equal to or greater than 4.0 pCi per l varied by zip code, ranging from 0 percent to 90 percent.

5.4 IMPACTS OF CHLORIDE SALTS ON DRINKING WATER

High concentrations of chloride salts can reduce the suitability of water for human consumption. In addition to producing the health effects discussed previously in this Chapter, additions of salts can reduce the aesthetic quality of drinking water. Water has a salty taste when the concentration of chloride exceeds about 250 mg/l or the concentration of sodium exceeds about 200 mg/l.[865] These thresholds can vary among individual people.

The USEPA and the State of Wisconsin have issued guidelines regarding the appropriate levels of chloride and sodium in drinking water.[866] Both the Agency and the State have set a secondary drinking water standard for chloride of 250 mg/l. In addition, an advisory from the USEPA recommends that sodium concentrations in drinking water not exceed 30 to 60 mg/l, based on taste.

Several studies have reported chloride contamination of drinking water. A study in New York found that 24 percent of the private wells sampled in the study area were contaminated with deicing salt and 21 percent of the wells sampled in the study area had chloride concentrations in excess of 250 mg/l.[867] The highest concentrations of chloride were observed in wells down gradient of a road salt storage barn. The median chloride concentration in these wells was 228 mg/l with a maximum concentration of 1,401 mg/l. Elevated chloride concentrations were also observed in samples from wells within about 100 feet of a major highway. The median chloride concentration in these wells was 116 mg/l, with a maximum concentration in excess of 500 mg/l. The median chloride concentration in wells near minor roads was 70 mg/l; however, concentrations of chloride in some of these wells were still quite high with the maximum concentration reported being in excess of 400 mg/l. About 70 percent of the participants in the study reported that they had stopped drinking their well water due to aesthetic and safety concerns.

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[860] *P.D. Warrington,* Roadsalt and Winter Maintenance for British Columbia Municipalities: Best Management Practices to Protect Water Quality, *British Columbia Ministry of Water, Land and Air Protection, 1998.*

[861] *L.A. McNaboe, G.A. Robbins, and M.E. Dietz, "Mobilization of Radium and Radon by Deicing Salt Contamination of Groundwater."* Water, Air, and Soil Pollution*, 228:94, 2017.*

[862] *R.W. Field et al., "Residential Radon Gas Exposure and Lung Cancer: The Iowa Lung Cancer Study,"* American Journal of Epidemiology*, 151:1,091-1,102, 2000.*

[863] *U.S. Environmental Protection Agency,* EPA Assessment of Risks from Radon in Homes*, EPA-402-R-03-003, June 2003.*

[864] *Wisconsin Department of Health Services, Wisconsin Indoor Radon Test Results, wi-dhs.maps.arcgis.com/apps/webappviewer/index.html?id=68f3a3e068854810b626d002ce47aff4, accessed June 7, 2023.*

[865] *Health Canada,* Guidelines for Canadian Drinking Water Quality (6th Edition)*, 1996.*

[866] Ibid.

[867] *Pieper et al. 2018,* op. cit.

The New York study also conducted a spatial analysis to estimate the likely number of private wells in the State that might potentially be impacted by deicing salt contamination. Based on the results of this analysis, the study concluded that about 35,000 wells, or two percent of the private wells in the State, could potentially be impacted by salt contamination from salt storage facilities. Similarly, the study concluded that about 460,000 wells, or 24 percent of the private wells in the State, could potentially be impacted by contamination from road salt applications. This deicing contamination of private wells may not be unique to New York. A study in Minnesota showed that about 30 percent of the wells tested in the Twin Cities metropolitan area exceeded the State standard for chloride.[868]

Similar chloride contamination of private wells has been reported in Wisconsin. One study monitored the impact of construction of a subdivision on groundwater in Dane County, about 15 miles northeast of Madison.[869] Monitoring wells were installed at the site in 2001, prior to the construction of the subdivision. Following construction of 18 homes in 2003, some domestic wells were also monitored through 2014. Concentrations of chloride increased over time in the 12 most frequently monitored domestic drinking water wells. Peak chloride concentrations in four of these wells exceeded 200 mg/l. In two of the wells, peak chloride concentration exceeded 400 mg/l. The Dane County study concluded that the increases in chloride concentrations in the wells was likely due to the increased use of deicing salts in and near the subdivision as well as effluent from onsite wastewater treatment systems. The effluent was assumed to include elevated concentrations of chloride due to the use of water softeners.

A 2016 search of the WDNR Public Water System database found 46 wells statewide that had reported concentrations of chloride over 100 mg/l and concentrations of sodium over 20 mg/l.[870] The areas in which these public water supply wells were located aligned well with areas experiencing heavy applications of road salt. This search found that two wells in Waukesha County were shut down in 2016 when drinking water chloride concentrations exceeded 400 mg/l. The search also found that most of the public drinking water system wells in the State had not been sampled for chloride over the previous 10 to 20 years.

Some municipal wells in the Southeastern Wisconsin Region may be impacted by contamination with chloride salts. Commission staff reviewed recent Consumer Confidence Reports for 69 municipal water utilities in the Region. These reports contain information on the quality and safety of the water provided by the utilities and are required to be provided annually to their customers. One utility in the Region reported that the chloride concentration in the water it provides was greater than 250 mg/l. Six more utilities reported chloride concentrations between 200 mg/l and 250 mg/l. These numbers may be underestimates as only 46 utilities reported the concentration of chloride in their water. In addition, 34 utilities reported providing water with sodium concentrations in excess of 20 mg/l, including one that reported sodium concentration greater than 200 mg/l. It should also be noted that since conventional water softeners work by exchanging calcium and magnesium ions in water for sodium on the ion exchange resin, residents in the Region who soften their water are likely exposed to higher concentrations of sodium than those in the public water supply.

Wells in at least two types of locations appear to be sensitive to contamination from deicing salts. First, high concentrations of deicing salts often occur in wells located downgradient from salt storage facilities. For instance, a study in New York found concentrations of chloride as high as 1,800 mg/l and concentrations of sodium as high as 860 mg/l in such wells.[871] Second, wells near roads, especially those near roads at lower elevations or downgradient of road networks often have relatively high chloride concentrations. For example, a study of 4,319 domestic wells in Vermont found that wells within about 330 feet of roads had

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[868] *S. Kroening and M. Ferry,* The Condition of Minnesota's Groundwater, 2007-2011*, Minnesota Pollution Control Agency wq-am1-06, 2013.*

[869] *K.R. Bradbury, T.W. Rayne, and J.J. Krause,* Impacts of a Rural Subdivision on Groundwater: Results of a Decade of Monitoring*, Wisconsin Geological and Natural History final report to the Wisconsin Department of Natural Resources, October 2015.*

[870] *J. Jansen,* Chlorides in Groundwater: A Rising Concern*, Presentation at the Fox River Summit, Burlington, Wisconsin, March 17, 2022.*

[871] *V.R. Kelly et al., "The Distribution of Road Salt in Private Drinking Water Wells in a Southeastern New York Suburban Township,"* Journal of Environmental Quality*, 47:445-451, 2018.*

significantly higher chloride concentrations than those that were farther away.[872] This study found that chloride contamination of wells near roads was especially common in urban and densely populated areas.

As mentioned in the previous section on the release of metals from drinking water infrastructure and plumbing, elevated concentrations of chloride salts in drinking water can lead to corrosion of water supply infrastructure and plumbing. This impact was discussed in Chapter 4 of this Report. The fact that many water systems are not regularly sampling for chlorides in the water they provide to the public may make it more difficult to identify other potential health issues. Corrosion can cause the release of lead from water mains, water supply service lines, interior plumbing, fittings, and solder that are not lead-free. While utilities are required to inventory water mains and water service lines that contain lead and to conduct monitoring at the taps of customers with lead service lines, no monitoring is required based on the possibility older buildings may have lead-containing interior plumbing. Regular monitoring of chloride and chloride-sulfate mass ratios in water systems at the tap could provide a preliminary way to evaluate the potential for lead release in buildings with older plumbing.

While it is technically feasible to remove chloride and associated cations from drinking water at a water treatment plant or wellhead using membrane filtration methods such as reverse osmosis, such treatment can drastically increase costs. Table 5.2 shows estimated capital and annual operation and maintenance costs for adding membrane filtration to water treatment plants with three different capacities. It should also be noted that membrane filtration produces a waste brine that requires disposal. Depending on the method used, such disposal may return the chloride salts to the environment. Disposal of this brine can also impact plant operating costs. In general, producing a higher-concentration brine reduces disposal costs; however, producing such a brine increases the energy costs associated with membrane filtration. More information on water treatment techniques for removing chlorides from water can be found in the Chloride Study State-of-the-Art technical report.[873]

5.5 IMPACTS OF CHLORIDE SALTS ON AGRICULTURE

As described in Chapter 2 of this report, introduction of chloride salts into the environment can increase the salinity of soil and water. This salinity increase can impact agriculture, reducing the yields of many crops. At high enough salinity, chloride salts can make soils unsuitable for agricultural activities.

Stress from salinity in soil can reduce crop growth and yields. Electrical conductivity is an indicator of soil salinity and can be measured as the specific conductance of water samples extracted from saturated soil during the maximum period of plant growth. Table 5.3 shows the soil specific conductance at which several crops experience 10, 25, and 50 percent reductions in yields. The specific conductance at which a particular level of yield reduction occurs varies among crops. Vegetable crops are generally more sensitive to soil salinity than field crops and forage crops. For most vegetables, the threshold of specific conductance in soil at which damage occurs to the crop is less than 2,500 microSiemens per cm (μS/cm).[874]

Salinity in irrigation water can also reduce crop yields. Yield impacts occur at relatively low levels of salinity and tend to rise at a near linear rate with water salinity.[875] Table 5.4 shows the thresholds of specific conductance in irrigation water above which crop yields of several vegetables are reduced. These thresholds tend to be lower than the thresholds for specific conductance in soil at which the same vegetables experience yield reductions of about 10 percent (compare Tables 5.3 and 5.4). The impact of crop reductions due to salinity in irrigation water can be substantial. One study that used a predictive model estimated that water salinity annually reduces global agricultural production by enough to feed about 170 million people.[876]

[872] *J.P. Levitt and S.L. Larsen,* Groundwater Chloride Concentrations in Domestic Wells and Proximity to Roadways in Vermont*, U.S. Geological Survey Open-File Report No. 2019-1148, 2020.*

[873] *SEWRPC Technical Report No. 66,* State of the Art of Chloride Management*, in preparation.*

[874] *R.M. Almeida Machado and R.P. Serralheiro, "Soil Salinity: Vegetable Crop Growth. Management Practices to Prevent and Mitigate Soil Salinization,"* Horticulturae*, 3:30, 2017.*

[875] *D. Russ et al.,* Salt of the Earth: Quantifying the Impact of Water Salinity on Global Agricultural Productivity, *The World Bank, Washington, D.C. 2019.*

[876] Ibid.

Direct salt contact on the above ground portions of plants can also reduce crop yields. Examples of this include reduced yields in blueberries and peaches and reduced number of flowers and flower buds on trees. These examples are discussed in the section on the impacts of chloride salts on terrestrial plants in Chapter 3 of this Report.

In addition to reducing the size of crop yields, stress from chloride salts can increase the fraction of crop yields that are unmarketable due to damage. For example, irrigation with salt contaminated water enhances blossom-end rot in plants like tomatoes, peppers, and eggplants.[877]

Table 5.2
Estimated Capital and Annual Operation and Maintenance Costs for Implementing Membrane Filtration at Drinking Water Treatment Plants

Plant Capacity (million gallons per day)	Capital Cost (dollars)	Annual Operations and Maintenance Cost Operating at 35 Percent of Capacity (dollars)
1	6,470,000	124,000
5	20,000,000	244,000
10	36,100,000	455,000

Note: Cost estimates were developed using the cost curve in Appendix A of SEWRPC Technical Report No. 43, *State-of-the-Art Water Supply Practices*, July 2007 and were updated from 2007 to 2022 dollars using Engineering News Record Construction Cost Index of 9,986.58 for 2007 and 16,171.31 for 2022.

Source: SEWRPC

There are several ways through which elevated concentrations of chloride salts in soil and water and physical contact with chloride salts can interfere with crop growth. These are discussed in detail in Chapter 2 and 3 of this report. Briefly, these mechanisms include:

- Degradation of soil structure
- Displacement of other nutrients
- Salt withdrawing water from surrounding soil
- Salt increasing plant energy requirements for extracting water and nutrients from soil
- Interference with chlorophyll production and photosynthesis
- Toxicity effects of chloride salts
- Physical damage to plants

5.6 AESTHETIC, RECREATIONAL, AND OTHER IMPACTS OF CHLORIDE SALTS

Elevated levels of chloride in the environment can potentially affect other human activities. These effects include impacts on aesthetic attributes and recreational potential of both natural and built environments. Unfortunately, few data are available to assess these chloride impacts.

Impacts on Fishing

Increases in salinity can potentially compromise the recreation and aesthetic values of freshwater aquatic systems.[878] As discussed in Chapter 3 of this Report, fishing is an important outdoor recreation activity in Wisconsin. The Wisconsin Department of Natural Resources (WDNR) estimates that fishing generates almost $2.3 billion in economic activity annually. Reductions in habitat quality and biodiversity due to elevated concentrations of chloride salts in streams, rivers, and lakes could potentially reduce the quality of fisheries and reduce the recreational experience of residents and tourists. This could occur directly through the effects of chloride salts on the fish and indirectly through impacts to organisms that serve as food resources to fish or provide important habitat structure. Examples of these effects are discussed in Chapter 3 of this Report.

[877] *Almeida Machado and Serralheiro 2017,* op. cit.

[878] *M. Cañedo-Argüelles Iglesias, "A Review of Recent Advances and Future Challenges in Freshwater Salinization,"* Limnetica*, 39:185-211, 2020.*

Aesthetic Impacts to the Environment

Applications of chloride salts can also cause aesthetic damage in terrestrial environments. One study estimated the cost of aesthetic damage to roadside trees in the Adirondack Forest Preserve in New York State as being about $157 per ton of road salt applied (2022 dollars).[879,880] In a second study, the New York State Department of Transportation estimated a cost of about $13,700 per mile (2022 dollars) to replant and re-establish natural vegetation along a two-mile section of highway in the Adirondack Mountains that had been damaged by applications of road salt.[881]

Another study used a simulation model of impacts on surface waters and forests to estimate the annual reduction of environmental value due to application of road salts.[882] This study concluded that these environmental value reductions were on the order of $3,140 per lane mile per year (2022 dollars). Using this estimate and salt application and other data from the Twin Cities Metropolitan Area (TCMA), a second study estimated that this environmental value reduction was equivalent to about $230 to $310 per ton of salt applied.[883] The calculation for the lower cost in this range includes estimates of all salt applied within the TCMA, while the higher cost in this range excludes bulk and packaged salt applied by private companies.

The cost estimates given in the previous two paragraphs should be interpreted with caution. They are based on limited data from a few examples in a single part of the country. It is not certain how representative they may be of similar costs in Wisconsin. Still, they give a rough sense of the order of magnitude of aesthetic damage to roadside vegetation and reductions of environmental value that may occur due to application of deicing salt.

Table 5.3
Soil Specific Conductance in MicroSiemens per Centimeter at Which Reduced Crop Yields Can Be Expected[a]

	Percent Yield Reduction		
Crop	10	25	50
Field Crops			
Barley	11,900	15,800	17,500
Sugar beets	10,000	13,000	16,000
Safflower	7,000	11,000	14,000
Wheat	7,100	10,000	14,000
Sorghum	5,900	9,000	11,900
Soybean	5,200	6,900	9,000
Rice	5,100	5,900	8,000
Corn	5,100	5,900	7,000
Broad bean	3,100	4,200	6,200
Beans	1,100	2,100	3,000
Vegetable Crops			
Beets	8,000	9,700	11,700
Spinach	5,700	6,900	8,000
Tomato	4,000	6,600	8,000
Broccoli	4,000	5,900	8,000
Cabbage	2,500	4,000	7,000
Potato	2,500	4,000	6,000
Corn	2,500	4,000	6,000
Sweet potato	2,500	3,700	6,000
Lettuce	2,000	3,000	4,800
Bell pepper	2,000	3,000	4,800
Onion	2,000	3,400	4,000
Carrot	1,300	2,500	4,200
Bean	1,300	2,000	3,200
Forage Crops			
Tall wheatgrass	10,900	15,100	18,100
Crested wheatgrass	5,900	11,000	18,100
Tall fescue	6,800	10,400	14,700
Barley hay	8,200	11,000	13,500
Perennial rye	7,900	10,000	13,000
Beardless wild rye	3,900	7,000	10,800
Alfalfa	3,000	4,900	8,200
Clovers	2,100	2,500	4,200

[a] *Values represent the specific conductance of saturated soil extracts during the period of maximum plant growth.*

Source: L. Bernstein, Salt Tolerance of Plants, *U.S. Department of Agriculture Information Bulletin 283, 1964.*

[879] *D.F. Vitaliano, "An Economic Assessment of the Social Costs of Highway Salting and the Efficiency of Substituting a New Deicing Material,"* Journal of Policy Analysis and Management*, 11:397-418, 1992.*

[880] *This cost estimates in this section were adjusted to 2022 dollars using the U.S. Bureau of Labor Statistics Consumer Price Index.*

[881] *T. Lindberg, S. Lorey, and B. Houseal,* Low Sodium Diet: Curbing New York's Appetite for Damaging Road Salt, *Adirondack Council, 2009.*

[882] *D.L. Kelting and C.L. Laxson,* Review of Effects and Costs of Road De-icing with Recommendations for Winter Road Management in the Adirondack Park, *Adirondack Watershed Institute Report No. AWI2010-01, Paul Smith's College, February 2010.*

[883] *C. Dindorf, C. Fortin, B. Asleson, and J. Erdmann,* The Real Cost of Salt Use for Winter Maintenance in the Twin Cities Metropolitan Area, *Minnesota Pollution Control Agency, wq-iw11-06bb, October 2014.*

Impacts on Building Cleaning

Applications of road salt can also affect the aesthetics inside buildings. This can result in additional costs for maintenance and cleaning to remove salt deposited inside buildings during winter months. One study estimated these costs for a large urban university.[884] Dalhousie University is located on about 60 acres in Halifax, Nova Scotia, Canada. In 2022, about 21,000 students were enrolled on this campus. In addition, this school employed about 2,000 full-time and part-time staff. Based on interviews with maintenance staff, the study estimated that the costs in 2004 of cleaning and maintenance to address damage from salt to floors and baseboards were about 15,000 Canadian dollars (Can$). These costs included those associated with cleaning floors, baseboards, walls, mats, and carpets. University staff also reported annually spending an additional Can$1,000 to Can$2,000 during the winter on waxes and sealants for floors. Converting these estimates to U.S. dollars and adjusting for inflation suggests that annual cost for a similar facility in the U.S. would be about $19,200 to $20,400.[885] This annual cost for building maintenance estimate should be interpreted with caution as it is based on estimated costs from one facility. In addition, conversions of costs from one currency to another based on exchange rates ignore the fact that wage rates and prices of individual goods may vary greatly among countries. In addition, cleaning and maintenance costs are likely to be partially dependent on factors such as the rate of salt application, the amount of foot traffic through individual buildings, and the number of winter storms occurring at individual sites.

Table 5.4
Specific Conductance Thresholds for Irrigation Water Causing Reduced Vegetable Yields

Vegetable	Threshold (μS/cm)
Asparagus	2,700
Red beet	2,700
Broccoli	1,900
Cauliflower	1,900
Tomato	1,700
Spinach	1,300
Celery	1,200
Pepper	1,000
Potato	1,100
Onion	800
Bean	700
Carrot	700
Eggplant	700
Strawberry	700

Source: P.M Almeida Machado and R.P Serralheira, "Soil Salinity: Effect on Vegetable Crop Growth. Management Practices to Prevent and Mitigate Soil Salinization," Horticulturae, *3:30, 2017.*

Impacts on Pets

Deicing salts can pose hazards to pets that are exposed to them. Cats and dogs walking on roads, sidewalks, and driveways that have been treated with deicers can collect these salts on their paws and fur. Casual exposures to salt can cause irritation to animal paws. Depending on the deicer used and the amount of exposure, this irritation may consist of dryness, cracking, or chemical burns.

Pets may experience other hazards if they lick deicing salts off their paws and fur or drink salt-contaminated water. While ingestion of small amounts of chloride-based deicers may not be harmful, ingestion of larger amounts can lead to high blood concentrations of sodium that result in thirst, salivation, vomiting, diarrhea, and lethargy. Ingestion of larger amounts of deicing salts can lead to more severe consequences such as convulsions and kidney damage. A lethal dose of sodium chloride for dogs is about two grams per pound.[886] This is the equivalent of a tablespoon of salt for a seven-pound dog. The American Society for the Prevention of Cruelty to Animals noted that in 1998 more than 50 cases of poisoning to animals by deicing salts were reported to their animal poison control center.[887] The toxicity of chloride salts for vertebrate animals is discussed in Chapter 3 of this report.

Impacts on Industrial Use of Water

The introduction of chloride salts into the environment can increase the salinity of water. Water with increased salinity may not be suitable for some industrial uses. Salt in water can also damage some equipment. In addition, salt may interfere with chemical reactions that occur during the production of some types of products.

[884] *A. Campbell et al.,* Feasibility Analysis of the Deicing Methods at Dalhousie University, *Dalhousie University, April 2004.*

[885] *The average exchange rate between U.S. and Canadian dollars in 2004 was $1.00 = Can$1.30. This was adjusted to 2022 dollars using a multiplier of 1.5596 based on the U.S. Bureau of Labor Statistics Consumer Price Index.*

[886] *Bryan Ray,* Be Salt Wise and Pet Smart, *Wisconsin Salt Wise, www.youtube.com/watch?v=QI8s-i5BniY, January 12, 2021.*

[887] *L.A. Hautekeete,* Ice Melts Are Health Hazards, *American Society for the Prevention of Cruelty to Animals, www.aspcapro.org/sites/default/files/u-toxbrief_2000.pdf, accessed June 15, 2023.*

The concentration at which water becomes unsuitable for industrial uses varies among industries. Table 5.5 shows critical concentrations thresholds above which saline water is not suitable for several industries. For some industries, such as in the textile industry, water becomes unsuitable at relatively low salinity. Other industries, such as in the petroleum industry, are able to use water until it reaches a higher salinity.

Table 5.5
Critical Levels of Salinity for Certain Industries[a]

Industry	Salinity (mg/l)
Textiles	100
Pulp and paper	200-500
Food (general)	850
Canning	850
Brewing, distilling	500-1,000
Chemical	2,500
Petroleum	3,500

[a] *These industrial uses are generally affected by salinity and not chloride per se; however, contamination of water with chloride salts increases salinity which can lead to the water being unsuitable for industrial uses.*

Source: W.D. Williams, "Salinization of Rivers and Streams: An Important Environmental Hazard," Ambio, *16:180-185, 1987.*

5.7 SUMMARY

Chloride salts provide several benefits to humans. These benefits include:

- Use of chemical deicers reduce the risk of traffic accidents during inclement winter weather
- Deicer use also reduces the risk of slip and fall accidents on driveways, sidewalks, parking lots, steps, and ramps
- Ion exchange water softeners, which are recharged using a sodium chloride brine, protect plumbing from the effects of scale produced by hard water
- Use of potassium chloride fertilizer can improve crop yields

Chloride salts are also associated with several adverse impacts on human activities. The adverse effects of chloride salts on human health include:

- Ingestion of excess sodium can cause high blood pressure, which is a major factor causing strokes, heart failure, kidney disease, and other ailments
- Ingestion of excess sodium can contribute to osteoporosis in post-menopausal women
- Elevated concentrations of chloride salts in water can result in release of heavy metals, which are toxic substances, from sediment, rock, and drinking water infrastructure
- Deicing salts are a constituent of fine particulate matter in the atmosphere ($PM_{2.5}$) which contributes to lung cancer and other respiratory ailments
- Upon contact, chloride salts can cause irritation to skin and eyes

Chloride salts can also degrade the aesthetics of the natural and built environment. Examples of this include:

- Chloride imparts a salty taste to water at a concentration of about 250 mg/l
- Sodium imparts a salty taste to water at a concentration of about 200 mg/l
- Chloride salts can degrade roadside aesthetics by damaging adjacent vegetation
- Use of deicing salts can increase costs of cleaning and maintenance of building interiors during winter months

Other effects of chloride salts on human activities include:

- Elevated concentrations of chloride salts in soil and irrigation water can reduce crop yields
- Through their effects on organisms, elevated concentrations of chloride salts in lakes, streams, and rivers can reduce the quality of fisheries, thereby reducing recreational opportunities
- Deicing salts can cause medical issues for pets
- Increased salinity can make water unsuitable for some industrial uses

APPENDICES

APPENDIX A

ACRONYMS AND ABBREVIATIONS

°F	Degrees Fahrenheit
^{222}Rn	Radon-222 isotope
^{226}Ra	Radium-226 isotope

A

ACR	Alkali-carbonate reaction
AgCl	Silver chloride
Al^{3+}	Aluminum ion
$AlCl_3$	Aluminum chloride
ALE	Lead action level
ASR	Alkali-silica reaction

B

BCL	Battelle Columbus Laboratories
BOD	Biochemical oxygen demand

C

Ca^{2+}	Calcium ion
$CaCl_2$	Calcium chloride
$CaCO_3$	Calcite, calcium carbonate
Can$	Canadian dollars
C-S-H	Calcium-silicate-hydrate
Cl^-	Chloride ion
CMA	Calcium magnesium acetate
CN^-	Cyanide ion
CO_2	Carbon dioxide
CPI	Consumer Price Index
CSMR	Chloride-sulfate mass ratio

D

DOC	Dissolved organic carbon

E

Eh	Oxidation-reduction potential
E. coli	Escherichia coli
EPT	Ephemeroptera, Plecoptera, Trichoptera (mayflies, stoneflies, and caddisflies)

F

Fe^0	Metallic iron
Fe^{2+}	Iron (II) ion
Fe^{3+}	Iron (III) ion
Fe_2O_3	Ferric oxide
Fe_3O_4	Magnetite
$FeCl_3$	Ferric chloride
$Fe(Fe_3(CN)_6)_3$	Ferric ferrocyanide
FeO	Ferrous oxide
$Fe(OH)_3$	Ferric hydroxide
FeS	Iron sulfide
FeS_2	Pyrite
FHWA	Federal Highway Administration

G

GDP	Gross domestic product
GNP	Gross national product

H

H^+	Hydrogen ion
H_2CO_3	Carbonic acid
HCN	Hydrogen cyanide
HCO_3^-	Bicarbonate ion
$HgCl_2$	Mercurous chloride

K

K^+	Potassium ion
KCl	Potassium chloride
kg	Kilograms
kg per acre	Kilograms per acre

L

lbs	Pounds
LC50	Concentration at which 50 percent of test organisms die

M

Mg^{2+}	Magnesium ion
mg	Milligrams
mg/kg	Milligrams per kilogram
mg/l	Milligrams per liter
$MgCl_2$	Magnesium chloride
mgd	Million gallons per day
$Mg(OH)_2$	Brucite, magnesium hydroxide
mm	Millimeters
mm Hg	Millimeters of mercury
M-S-H	Magnesium-silicate-hydrate
MVMT	Motor vehicle miles traveled

N

N_2	Nitrogen gas
N_2O	Nitrous oxide
Na^{2+}	Sodium ion
$Na_4Fe(CN)_6$	Sodium ferrocyanide
Na:Cl	Sodium to chloride ratio
NaCl	Sodium chloride
NaClO	Sodium hypochlorite
NBI	National Bridge Inventory
NBS	National Bureau of Standards
NH_4^+	Ammonium ion
Ni^{2+}	Nickel ion
NO_2^-	Nitrite
NO_3^-	Nitrate
NH_4^+	Ammonium ion

P

$PbCl_2$	Lead chloride
pCi per l	Picocuries per liter
$PM_{2.5}$	Airborne particulate with a diameter of 2.5 micrometers or less
ppm	Parts per million

R

Ra^{2+}	Radium ion

S

SCN^-	Thiocyanate ion
SEWRPC	Southeastern Wisconsin Regional Planning Commission
SO_4^{2-}	Sulfate
SRP	Soluble reactive phosphorus
stu	Standard units

T

TCMA	Twin Cities Metropolitan Area
TRB	Transportation Research Board

U

USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

V

V	Volts

W

WDNR	Wisconsin Department of Natural Resources
WisDOT	Wisconsin Department of Transportation
WWTP	Wastewater treatment plant

μ

μg/dl	Micrograms per deciliter
μg/l	Microgram per liter
μS/cm	MicroSiemens per centimeter

APPENDIX B

ACUTE TOXICITY OF CHLORIDE COMPOUNDS

Table B.1
Acute Toxicity of Chloride Compounds to Freshwater Aquatic Organisms

Species	Common Name	Cation[a]	Cation Concentration (mg/l)	Chloride Concentration (mg/l)	Exposure Time (hours)	Response[b]	Reference[c]
Salvelinus fontinalis	Brook trout	Na^+	19,670	**30,330**	0.25	LC50	Phillips, 1944
Daphnia magna	Water flea	K^+	721	**654**	2.00	LC50	Densmore *et al.*, 2018
Daphnia magna	Water flea	K^+	271	**246**	4.00	LC50	Densmore *et al.*, 2018
Lepomis macrochirus	Bluegill	Na^+	7,868	**12,132**	6.00	LC47	Waller, *et al.*, 1996
Oncorhynchus mykiss	Rainbow trout	Na^+	7,868	**12,132**	6.00	LC40	Waller, *et al.*, 1996
Labeo rohita	Rohu carp (fingerlings)	Ca^{2+}	4,425	**7,830**	6.00	LC50	Mallick, *et al.*, 2014
Chironomus attenuatus	Midge	Na^+	3,932	**6,063**	6.00	LC50	Thornton and Sauer, 1972
Labeo rohita	Rohu carp (spawn)	Ca^{2+}	2,613	**4,624**	6.00	LC50	Mallick, *et al.*, 2014
Labeo rohita	Rohu carp (eggs)	Ca^{2+}	1,349	**2,388**	6.00	LC50	Mallick, *et al.*, 2014
Labeo rohita	Rohu carp (fingerlings)	Ca^{2+}	4,112	**7,275**	12.00	LC50	Mallick, *et al.*, 2014
Labeo rohita	Rohu carp (fry)	Ca^{2+}	3,559	**6,296**	12.00	LC50	Mallick, *et al.*, 2014
Labeo rohita	Rohu carp (spawn)	Ca^{2+}	1,985	**3,513**	12.00	LC50	Mallick, *et al.*, 2014
Labeo rohita	Rohu carp (eggs)	Ca^{2+}	838	**1,484**	12.00	LC50	Mallick, *et al.*, 2014
Labeo rohita	Rohu carp (eggs)	Ca^{2+}	387	**686**	18.00	LC50	Mallick, *et al.*, 2014
Caenorhabditis elegans	Round worm	Ca_{2+}	16,033	**28,367**	24.00	LC50	Tartara *et al.*, 1997
Gambusia affins	Mosquito fish	Mg^{2+}	4,776	**13,932**	24.00	LC50	Wallen *et al.*, 1957
Gambusia affins	Mosquito fish	Na^+	7,105	**10,955**	24.00	LC50	Wallen *et al.*, 1957
Lepomis macrochirus	Bluegill	Na^+	5,557	**8,568**	24.00	LC50	Dowden and Bennett, 1965
Lepomis macrochirus	Bluegill	Na^+	5,547	**8,553**	24.00	LC50	Doudoroff and Katz, 1953
Gambusia affins	Mosquito fish	Ca^{2+}	4,828	**8,542**	24.00	LC50	Wallen *et al.*, 1957
Carassius auratus	Goldfish	Na^+	5,409	**8,341**	24.00	LC50	Dowden and Bennett, 1965
Labeo rohita	Rohu carp (fingerlings)	Ca^{2+}	3,778	**6,684**	24.00	LC50	Mallick, *et al.*, 2014
Culex sp.	Mosquito	Na^+	4,131	**6,369**	24.00	LC50	Dowden and Bennett, 1965
Labeo rohita	Rohu carp (fry)	Ca^{2+}	3,523	**6,234**	24.00	LC50	Mallick, *et al.*, 2014
Lithobates sylvatica[d]	Wood frog (tadpoles)	Mg^{2+}	1,882	**5,488**	24.00	LC50	Harless *et al.*, 2011
Lepomis machrochirus	Bluegill	Ca^2	3,015	**5,335**	24.00	LC50	Dowden and Bennett, 1965
Lithobates sylvatica[d]	Wood frog	Na^+	3,588	**5,532**	24.00	LC50	Harless *et al.*, 2011
Pimephales promelas	Fathead minnow	Na^+	3,257	**5,023**	24.00	LC50	Mount *et al.*, 1997
Pimephales promelas	Fathead minnow	Na^+	3,116	**4,804**	24.00	LC50	Adelman *et al.*, 1976
Gambusia affins	Mosquito fish	K^+	5,233	**4,745**	24.00	LC50	Wallen *et al.*, 1957
Daphnia magna	Water flea	Na^+	3,050	**4,704**	24.00	LC50	Cowgill and Milazzo, 1990
Cirrhinius mrigalo	Mrigal carp (fry)	Na^+	2,950	**4,550**	24.00	LC50	Ghosh and Pal, 1969
Labeo rohoto	Rohu carp (fry)	Na^+	2,950	**4,550**	24.00	LC50	Ghosh and Pal, 1969
Catla catla	Major (Indian) carp (fry)	Na^+	2,950	**4,550**	24.00	LC50	Ghosh and Pal, 1969

Table continued on next page.

Table B.1 (Continued)

Species	Common Name	Cation[a]	Cation Concentration (mg/l)	Chloride Concentration (mg/l)	Exposure Time (hours)	Response[b]	Reference[c]
Streptocephalus probocideus	Fairy shirmp	Na^+	2,569	**3,961**	24.00	LC50	Calleja *et al.*, 1994
Microhyla ornata	Ornate narrow-mouthed frog (hind-limb tadpoles)	Na^+	2,550	**3,932**	24.00	LC50	Padhye and Ghate, 1992
Daphnia magna	Water flea	Na^+	2,510	**3,870**	24.00	LC50	Mount *et al.*, 1997
Ictalurus punctatus	Channel catfish (5.0-6.0 cm)	K^+	3,849	**3,489**	24.00	LC50	Durand-Hoffman, 1995
Ptychobranchus fasiolaris	Kidneyshell mussel (glochidia)	Na^+	2,215	**3,416**	24.00	EC50	Gillis, 2011
Physa heterostropha	European physa snail	Na^+	2,176	**3,354**	24.00	LC50	Wurtz and Bridges, 1961
Oncorhynchus mykiss	Rainbow trout	Na^+	2,162	**3,334**	24.00	LC50	Kostecki and Jones, 1983
Bufo boreas	Boreal toad	Mg^{2+}	1,121	**3,271**	24.00	LC50	Lewis, 1999
Lithobates sylvatica[d]	Wood frog (tadpoles)	Ca^{2+}	1,751	**3,099**	24.00	LC50	Harless *et al.*, 2011
Lymnaea sp.	Pond snail (eggs)	Ca^{2+}	1,620	**2,865**	24.00	LC50	Dowden and Bennett, 1965
Pimephales promelas	Fathead minnow	Mg^{2+}	899	**2,621**	2400	LC50	Mount *et al.*, 1997
Lepomis macrochirus	Bluegill	K^+	2,885	**2,615**	24.00	LC50	Dowden and Bennett, 1965
Anodonta anatina	Duck mussel	Na^+	1,624	**2,505**	24.00	LC50	Beggel and Geist, 2015
Labeo rohita	Rohu carp (spawn)	Ca^{2+}	1,347	**2,384**	24.00	LC50	Mallick, *et al.*, 2014
Microhyla ornata	Ornate narrow-mouthed frog (late gastrula stage)	K^+	2,623	**2,378**	24.00	LC50	Padhye and Ghate, 1992
Lithobates sylvatica	Wood frog (Gosner stage 33 tadpoles)	Na^+	1,479	**2,281**	24.00	LC50	Copan, 2016
Brachionus calyciflorus	Rotifer	Na^+	1,440	**2,220**	24.00	LC50	Calleja *et al.*, 1994
Daphnia magna	Water flea	Na^+	1,420	**2,190**	24.00	LC50	Calleja *et al.*, 1994
Lithobates sylvatica	Wood frog (Gosner stage 29 tadpoles)	Na^+	1,361	**2,099**	24.00	LC50	Copan, 2016
Daphnia magna	Water flea	Ca^{2+}	1,174	**2,076**	24.00	LC50	Mount *et al.*, 1997
Daphnia magna	Water flea	Na^+	1,342	**2,070**	24.00	LC50	Dowden and Bennett, 1965
Lymnaea sp.	Pond snail (eggs)	Na^+	1,342	**2,070**	24.00	LC50	Dowden and Bennett, 1965
Ceriodaphnia dubia	Water flea	Na^+	1,330	**2,050**	24.00	LC50	Mount *et al.*, 1997
Villosa delumbis	Eastern creekshell mussel (glochidia)	Na^+	1,302	**2,008**	24.00	EC50	Bringolf *et al.*, 2007
Tubifex tubifex	Sludge worm	Na^+	1,250	**1,928**	24.00	EC50	Khangarot, 1991
Tubifex tubifex	Sludge worm	K^+	2,000	**1,813**	24.00	EC50	Khangarot, 1991
Villosa constricta	Notched rainbow mussel (glochidia)	Na^+	1,086	**1,674**	24.00	EC50	Bringolf *et al.*, 2007
Daphnia pulex	Water flea	Na^+	1,072	**1,652**	24.00	LC50	Cowgill and Milazzo, 1990
Ceriodaphnia dubia	Water flea	Na^+	1,072	**1,652**	24.00	LC50	Cowgill and Milazzo, 1990
Brachionus calyciflorus	Rotifer	Na^+	1,067	**1,645**	24.00	LC50	Elphick *et al.*, 2011
Elliptio complanata	Easter elliptio mussel	Na^+	1,050	**1,620**	24.00	EC50	Bringolf *et al.*, 2007
Lampsilis fasicola	Wavy-rayed lampmussel (glochidia)	Na^+	1,011	**1,559**	24.00	EC50	Bringolf *et al.*, 2007
Ceriodaphnia dubia	Water flea	Ca^{2+}	816	**1,444**	24.00	LC50	Mount *et al.*, 1997
Tubifex tubifex	Sludge worm	Ca^{2+}	814	**1,441**	24.00	EC50	Khangarot, 1991
Lampsilis siliquoidea	Fat mucket mussel (glochidia)	Na^+	927	**1,430**	24.00	EC50	Gillis, 2011

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Table B.1 (Continued)

Species	Common Name	Cation[a]	Cation Concentration (mg/l)	Chloride Concentration (mg/l)	Exposure Time (hours)	Response[b]	Reference[c]
Lampsilis fasicola	Wavy-rayed lampmussel (glochidia)	Na^+	902	**1,391**	24.00	EC50	Gillis, 2011
Lampsilis fasicola	Wavy-rayed lampmussel (glochidia)	Na^+	852	**1,313**	24.00	EC50	Gillis, 2011
Lampsilis fasicola	Wavy-rayed lampmussel (glochidia)	Na^+	820	**1,265**	24.00	EC50	Gillis, 2011
Daphnia magna	Water flea	Ca^{2+}	664	**1,174**	24.00	LC50	Dowden and Bennett, 1965
Pimephales promelas	Fathead minnow	K^+	1,293	**1,172**	24.00	LC50	Durand-Hoffman, 1995
Daphnia magna	Water flea	Mg^{2+}	398	**1,162**	24.00	LC50	Mount *et al.*, 1997
Lampsilis fasicola	Wavy-rayed lampmussel (glochidia)	Na^+	724	**1,116**	24.00	EC50	Gillis, 2011
Ceriodaphnia dubia	Water flea	Mg^{2+}	324	**946**	24.00	LC50	Mount *et al.*, 1997
Lymnaea sp.	Pond snails (eggs)	K+	1,018	**923**	24.00	LC50	Dowden and Bennett, 1965
Streptocephalus proboscideus	Fairy shrimp	K+	981	**889**	24.00	LC50	Calleja *et al.*, 1994
Lampsilis siliquoidea	Fat mucket mussel (glochidia)	Na^+	535	**825**	24.00	LC50	Hazelton *et al.*, 2013
Lampsilis cardium	Plain pocketbook mussel (glochidia)	Na^+	530	**817**	24.00	EC50	Gillis, 2011
Brachionus calyciflorus	Rotifer	K^+	886	**804**	24.00	LC50	Calleja *et al.*, 1994
Ligurnia recta	Black sandshell mussel (glochidia)	Na^+	496	**764**	24.00	LC50	Hazelton *et al.*, 2013
Lithobates sylvatica	Wood frog (Gosner stage 26 tadpoles)	Na^+	492	**758**	24.00	LC50	Copan, 2016
Salmo gairdneri	Rainbow trout (5.0-6.0 cm)	K^+	625	**566**	24.00	LC50	Durand-Hoffman, 1995
Pimephales promelas	Fathead minnow	K^+	498	**452**	24.00	LC50	Mount *et al.*, 1997
Notemigonus crysolucas	Golden shiner	K+	428	**388**	24.00	LC50	Durand-Hoffman, 1995
Lithobates sylvatica	Wood frog (Gosner stage 19 tadpoles)	Na^+	230	**354**	24.00	LC50	Copan, 2016
Daphnia magna	Water flea	K+	388	**352**	24.00	LC50	Mount *et al.*, 1997
Stizostedion vitreum	Walleye (1.5-2.5 cm)	K+	380	**344**	24.00	LC50	Durand-Hoffman, 1995
Lampsilis siliquoidea	Fat mucket mussel (glochidia)	Na^+	216	**334**	24.00	EC50	Bringolf *et al.*, 2007
Ceriodaphnia dubia	Water flea	K+	330	**300**	24.00	LC50	Mount *et al.*, 1997
Lampsilis fasicola	Wavy-rayed lampmussel (glochidia)	Na^+	185	**285**	24.00	EC50	Gillis, 2011
Lithobates sylvatica	Wood frog (Gosner stage 22 tadpoles)	Na^+	161	**248**	24.00	LC50	Copan, 2016
Daphnia magna	Water flea	K+	287	**261**	24.00	LC50	Calleja *et al.*, 1994
Epioblasma torulosa rangiana	Northern riffle shell mussel (glochidia)	Na^+	158	**244**	24.00	EC50	Gillis, 2011
Stizostedion canadense	Sanger	K+	262	**238**	24.00	LC50	Durand-Hoffman, 1995
Lampsilis siliquoidea	Fat mucket mussel (glochidia)	Na^+	109	**168**	24.00	EC50	Gillis, 2011
Daphnia magna	Water flea	K+	180	**163**	24.00	LC50	Dowden and Bennett, 1965
Labeo rohita	Rohu carp (eggs)	Ca^{2+}	92	**163**	24.00	LC50	Mallick *et al.*, 2014
Daphnia magna	Water flea	K+	145	**132**	24.00	LC50	Densmore *et al.*, 2018
Lampsilis fasicola	Wavy-rayed lampmussel (glochidia)	Na^+	73	**113**	24.00	EC50	Gillis, 2011
Dreissena polymorpha	Zebra mussel	K^+	72	**66**	24.00	LC50	Waller *et al.*, 1993
Dreissena polymorpha	Zebra mussel (0.5-1.5 cm)	K^+	72	**66**	24.00	LC50	Durand-Hoffman, 1995

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Table B.1 (Continued)

Species	Common Name	Cation[a]	Cation Concentration (mg/l)	Chloride Concentration (mg/l)	Exposure Time (hours)	Response[b]	Reference[c]
Dreissena polymorpha	Zebra mussel (2.0-2.5 cm)	K^+	53	**49**	24.00	LC50	Durand-Hoffman, 1995
Molliensia latipinna	Sailfin mollie	Na^+	2,536	**3,911**	25.00	LC50	Dowden and Bennett, 1965
Daphnia magna	Water flea	Na^+	1,517	**2,340**	25.00	LC50	Dowden and Bennett, 1965
Daphnia magna	Water flea	Ca^{2+}	1,273	**2,253**	25.00	LC50	Dowden and Bennett, 1965
Daphnia magna	Water flea	Mg^{2+}	866	**2,525**	25.00	LC50	Dowden and Bennett, 1965
Labeo rohita	Rohu carp (eggs)	Ca^{2+}	23	**41**	36.00	LC50	Mallick *et al.*, 2014
Gambusia affins	Mosquito fish	Mg^{2+}	4,521	**13,189**	48.00	LC50	Wallen *et al.*, 1957
Cyclops abyssorum	Cyclopoid copepod	Ca^{2+}	7,005	**12,395**	48.00	LC50	Baudouin and Scoppa, 1974
Caridina denticulata dendiculata	Cherry shrimp	Ca^{2+}	6,545	**11,580**	48.00	LC50	Baek *et al.*, 2014
Gambusia affins	Mosquito fish	Na^+	7,105	**10,955**	48.00	LC50	Wallen *et al.*, 1957
Molliensia latipinna	Sailfin mollie	Na^+	6,528	**10,067**	48.00	LC50	Dowden and Bennett, 1965
Gambusia affins	Mosquito fish	Ca^{2+}	4,828	**8,542**	48.00	LC50	Wallen *et al.*, 1957
Eudiaptomus padanus	Calanoid copepod	Ca^{2+}	4,008	**7,092**	48.00	LC50	Baudouin and Scoppa, 1974
Labeo rohita	Rohu carp (fingerling)	Ca^{2+}	3,688	**6,524**	48.00	LC50	Mallick *et al.*, 2014
Culex sp.	Mosquito	Na^+	4,034	**6,222**	48.00	LC50	Dowden and Bennett, 1965
Labeo rohita	Rohu carp (fry)	Ca^{2+}	3,193	**5,650**	48.00	LC50	Mallick *et al.*, 2014
Lithobates sylvatica[d]	Wood frog (tadpoles)	Mg^{2+}	1,859	**5,421**	48.00	LC50	Harless *et al.*, 2011
Daphnia hyalina	Water flea	Ca^{2+}	2,997	**5,303**	48.00	LC50	Baudouin and Scoppa, 1974
Lithobates sylvatica[d]	Wood frog (tadpoles)	Na^+	3,076	**4,744**	48.00	LC50	Harless *et al.*, 2011
Pimephales promelas	Fathead minnow	Na^+	3,025	**4,655**	48.00	LC50	Adelman *et al.*, 1976
Ameletus sp.	Brown dun mayfly	Na^+	2,738	**4,222**	48.00	LC50	Echols *et al.*, 2009
Daphnia magna	Water flea	Na^+	2,596	**4,004**	48.00	LC50	Schuytema *et al.*, 1997
Pimephales promelas	Fathead minnow	Na^+	2,561	**3,949**	48.00	LC50	Mount *et al.*, 1997
Lemna minor	Small duckweed	Na^+	2,529	**3,900**	48.00	EC50	Simmons, 2012
Daphnia magna	Water flea	Na^+	2,529	**3,900**	48.00	EC50	Goncalves *et al.*, 2007
Ecdyonurus levis	Little slate-winged dun mayfly	Ca^{2+}	2,191	**3,876**	48.00	LC50	Baek *et al.*, 2014
Cleon dipterum	Common wetland mayfly	Ca^{2+}	2,128	**3,776**	48.00	LC50	Baek *et al.*, 2014
Daphnia magna	Water flea	Na^+	2,156	**3,324**	48.00	LC50	Martinez-Jeronimo and Martinez-Jeronimo, 2007
Baetis tricaudatus	Blue-winged olive mayfly	Na^+	2,140	**3,300**	48.00	LC50	Lowell *et al.*, 1995
Bufo boreas	Boreal toad	Mg^{2+}	1,121	**3,271**	48.00	LC50	Lewis, 1999
Baetis tricaudatus	Blue-winged olive mayfly	Na^+	2,097	**3,233**	48.00	LC50	Lowell *et al.*, 1995
Physa heterostropha	European physa snail	Na^+	2,018	**3,112**	48.00	LC50	Wurtz and Bridges, 1961
Lithobates sylvaticad	Wood frog (tadpoles)	Ca^{2+}	1,704	**3,016**	48.00	LC50	Harless *et al.*, 2011
Daphnia magna	Water flea	Na^+	1,951	**3,009**	48.00	EC50	Abe *et al.*, 2014

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Table B.1 (Continued)

Species	Common Name	Cation[a]	Cation Concentration (mg/l)	Chloride Concentration (mg/l)	Exposure Time (hours)	Response[b]	Reference[c]
Daphnia magna	Water flea	Na^+	1,915	**2,954**	48.00	LC50	Struewing *et al.*, 2015
Daphnia magna	Water flea	Na^+	1,877	**2,893**	48.00	LC50	Mount *et al.*, 1997
Daphnia magna	Water flea	Na^+	1,821	**2,808**	48.00	LC50	Biesinger and Christensen, 1972
Daphnia magna	Water flea	Na^+	1,641	**2,530**	48.00	LC50	Biesinger and Christensen, 1972
Glyptotendipes tokunagai	Midge	Ca^{2+}	1,331	**2,355**	48.00	LC50	Baek *et al.*, 2014
Ligurnia recta	Black sandshell mussel (juveniles)	Na^+	1,475	**2,275**	48.00	LC50	Hazelton *et al.*, 2013
Villosa delumbis	Eastern creekshell mussel (glochidia)	Na^+	1,428	**2,202**	48.00	EC50	Bringolf *et al.*, 2007
Gammarus sobaegenis	Scud	Ca^{2+}	1,227	**2,171**	48.00	LC50	Baek *et al.*, 2014
Lampsilis siliquoidea	Fat mucket mussel (glochidia)	Na^+	1,404	**2,166**	48.00	LC50	Hazelton *et al.*, 2013
Lithobates sylvatica	Wood frog (Gosner stage 33 tadpoles)	Na^+	1,374	**2,118**	48.00	LC50	Copan, 2016
Pimephales promelas	Fathead minnow	Mg2+	725	**2,115**	48.00	LC50	Mount *et al.*, 1997
Lymnaea sp.	Pond snail (eggs)	Na^+	1,333	**2,055**	48.00	LC50	Dowden and Bennett, 1965
Labeo rohita	Rohu carp (spawn)	Ca^{2+}	1,151	**2,036**	48.00	LC50	Mallick *et al.*, 2014
Daphnia magna	Water flea	Na^+	1,302	**2,008**	48.00	LC50	Dowden and Bennett, 1965
Lymnaea sp.	Pond snail (eggs)	Ca^{2+}	1,117	**1,977**	48.00	LC50	Dowden and Bennett, 1965
Ceriodaphnia dubia	Water flea	Na^+	1,191	**1,836**	48.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Daphnia magna	Water flea	Na^+	1,174	**1,809**	48.00	LC50	Ghazy *et al.*, 2009
Ceriodaphnia dubia	Water flea	Na^+	1,154	**1,779**	48.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Lithobates sylvatica	Wood frog (Gosner stage 29 tadpoles)	Na^+	1,154	**1,779**	48.00	LC50	Copan, 2016
Daphnia magna	Water flea	Ca^{2+}	1,000	**1,770**	48.00	LC50	Mount *et al.*, 1997
Daphnia longispina	Water flea	Na^+	1,141	**1,759**	48.00	EC50	Goncalves *et al.*, 2007
Daphnia longispina	Water flea	Na^+	1,121	**1,729**	48.00	LC50	Leitao *et al.*, 2013
Daphnia longispina	Water flea	Na^+	1,109	**1,711**	48.00	LC50	Leitao *et al.*, 2013
Daphnia longispina	Water flea	Na^+	1,102	**1,698**	48.00	LC50	Leitao *et al.*, 2013
Ceriodaphnia dubia	Water flea	Na^+	1,031	**1,589**	48.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Villosa constricta	Notched rainbow mussel (glochidia)	Na^+	1,019	**1,571**	48.00	EC50	Bringolf *et al.*, 2007
Tubifex tubifex	Sludge worm	Na^+	1,016	**1,567**	48.00	EC50	Khangarot, 1991
Daphnia magna	Water flea	Ca^{2+}	867	**1,533**	48.00	EC50	DeGroot and Groeneveld, 1998
Maccaffertium modestum[e]	Cream cahill mayfly	Na^+	984	**1,517**	48.00	LC50	Roback, 1965
Ceriodaphnia dubia	Water flea	Na^+	985	**1,519**	48.00	LC50	Cowgill and Milazzo, 1990
Daphnia longispina	Water flea	Na^+	984	**1,517**	48.00	LC50	Leitao *et al.*, 2013
Daphnia longispina	Water flea	Na^+	976	**1,504**	48.00	LC50	Leitao *et al.*, 2013

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Table B.1 (Continued)

Species	Common Name	Cation[a]	Cation Concentration (mg/l)	Chloride Concentration (mg/l)	Exposure Time (hours)	Response[b]	Reference[c]
Ceriodaphnia dubia	Water flea	Na^+	966	**1,489**	48.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Ceriodaphnia dubia	Water flea	Na^+	909	**1,402**	48.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Ceriodaphnia dubia	Water flea	Na^+	880	**1,357**	48.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Ceriodaphnia dubia	Water flea	Na^+	879	**1,356**	48.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Elliptio complanata	Eastern elliptio mussel	Na^+	877	**1,353**	48.00	EC50	Bringolf *et al.*, 2007
Ceriodaphnia dubia	Water flea	Na^+	854	**1,317**	48.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Ceriodaphnia dubia	Water flea	Na^+	811	**1,250**	48.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Ceriodaphnia dubia	Water flea	Na^+	810	**1,249**	48.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Daphnia pulex	Water flea	Na^+	803	**1,239**	48.00	LC50	Gardner and Royer, 2010
Daphnia ambigua	Water flea	Na^+	787	**1,213**	48.00	LC50	Cowgill and Milazzo, 1991
Tubifex tubifex	Sludge worm	K^+	1,320	**1,197**	48.00	EC50	Khangarot, 1991
Ceriodaphnia dubia	Water flea	Na^+	773	**1,192**	48.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Ceriodaphnia dubia	Water flea	Na^+	771	**1,189**	48.00	LC50	Mount *et al.*, 2016
Ceriodaphnia dubia	Water flea	Ca^{2+}	661	**1,169**	48.00	LC50	Mount *et al.*, 2016
Ceriodaphnia dubia	Water flea	Na^+	748	**1,154**	48.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Daphnia pulex	Water flea	Na^+	713	**1,099**	48.00	LC50	Gardner and Royer, 2010
Ceriodaphnia dubia	Water flea	Na^+	693	**1,068**	48.00	LC50	Elphick *et al.*, 2011
Lampsilis fasicola	Wavy-rayed lampmussel (glochidia)	Na^+	685	**1,055**	48.00	EC50	Bringolf *et al.*, 2007
Daphnia magna	Water flea	Mg^{2+}	340	**990**	48.00	LC50	Mount *et al.*, 2016
Ceriodaphnia dubia	Water flea	Na^+	634	**977**	48.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Ceriodaphnia dubia	Water flea	Na^+	626	**964**	48.00	LC50	Cowgill and Milazzo, 1991
Daphnia magna	Water flea	Mg^{2+}	322	**941**	48.00	LC50	Biesinger and Christensen, 1972
Centroptilum triangulifer	Triangle small minnow mayfly	K^+	1,026	**931**	48.00	LC50	Struewing *et al.*, 2015
Ceriodaphnia dubia	Water flea	Na^+	558	**861**	48.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Pseudosida ramosa	Sida water flea	Na^+	543	**838**	48.00	LC50	Freitas and Rocha, 2011, 2011a

Table continued on next page.

Table B.1 (Continued)

Species	Common Name	Cation[a]	Cation Concentration (mg/l)	Chloride Concentration (mg/l)	Exposure Time (hours)	Response[b]	Reference[c]
Daphnia pulex	Water flea	Ca^{2+}	460	**815**	48.00	LC50	Biesinger and Christensen, 1972
Oncorhynchus mykiss	Rainbow trout	K^{+}	844	**766**	48.00	LC50	Waller *et al.*, 1993
Lymnaea sp.	Pond snail (eggs)	K^{+}	783	**709**	48.00	LC50	Dowden and Bennett, 1965
Tubifex tubifex	Sludge worm	Ca^{2+}	389	**688**	48.00	LC50	Khangarot, 1991
Daphnia magna	Water flea	Ca^{2+}	383	**679**	48.00	LC50	Khangarot and Ray, 1989
Ceriodaphnia dubia	Water flea	Mg^{2+}	225	**655**	48.00	LC50	Mount *et al.*, 2016
Lithobates sylvatica	Wood frog (Gosner stage 26 tadpoles)	Na^{+}	385	**593**	48.00	LC50	Copan, 2016
Daphnia similis	Water flea	K+	624	**566**	48.00	EC50	Utz and Bohrer, 2001
Daphnia similis	Water flea	K+	566	**514**	48.00	EC50	Utz and Bohrer, 2001
Daphnia magna	Water flea	Ca^{2+}	274	**485**	48.00	LC50	Dowden and Bennett, 1965
Pimephales promelas	Fathead minnow	K^{+}	477	**433**	48.00	LC50	Mount *et al.*, 1997
Daphnia magna	Water flea	Mg^{2+}	140	**409**	48.00	LC50	Biesinger and Christensen, 1972
Nitocra spinipes	Harpacticoid copepod	K^{+}	448	**406**	48.00	LC50	Bengtsson, 1978
Centroptilum triangulifer	Triangle small minnow mayfly	Na^{+}	259	**400**	48.00	LC50	Struewing *et al.*, 2015
Ictalurus punctatus	Channel catfish	K+	378	**342**	48.00	LC50	Waller *et al.*, 1993
Lampsilis siliquoidea	Fat mucket mussel (glochidia)	Na^{+}	220	**340**	48.00	EC50	Bringolf *et al.*, 2007
Daphnia magna	Water flea	K^{+}	367	**333**	48.00	LC50	Struewing *et al.*, 2015
Daphnia similis	Water flea	K^{+}	362	**328**	48.00	EC50	Utz and Bohrer, 2001
Daphnia magna	Water flea	K^{+}	346	**314**	48.00	LC50	Mount *et al.*, 1997
Ceriodaphnia dubia	Water flea	K^{+}	330	**300**	48.00	LC50	Mount *et al.*, 1997
Ceriodaphnia dubia	Water flea	K^{+}	304	**275**	48.00	LC50	Struewing *et al.*, 2015
Lithobates sylvatica	Wood frog (Gosner stage 22 tadpoles)	Na^{+}	139	**214**	48.00	LC50	Copan, 2016
Daphnia magna	Water flea	K^{+}	177	**160**	48.00	LC50	Dowden and Bennett, 1965
Daphnia magna	Water flea	K^{+}	166	**151**	48.00	LC50	Biesinger and Christensen, 1972
Lithobates sylvatica	Wood frog (Gosner stage 19 tadpoles)	Na^{+}	95	**147**	48.00	LC50	Copan, 2016
Daphnia magna	Water flea	K^{+}	103	**93**	48.00	LC50	Densmore *et al.* 2018
Daphnia magna	Water flea	Ca^{2+}	52	**91**	48.00	LC50	Biesinger and Christensen, 1972
Daphnia magna	Water flea	K^{+}	93	**84**	48.00	LC50	Biesinger and Christensen, 1972
Dreissena polymorpha	Zebra mussel	K^{+}	79	**71**	48.00	LC50	Waller *et al.*, 1993
Dreissena polymorpha	Zebra mussel	K^{+}	77	**70**	48.00	LC50	Waller *et al.*, 1993
Labeo rohita	Rohu carp (eggs)	Ca^{2+}	21	**38**	48.00	LC50	Mallick *et al.*, 2014
Psuedosida ramosa	Sida water flea	K^{+}	18	**16**	48.00	LC50	Freitas and Rocha, 2011
Psuedosida ramosa	Sida water flea	K^{+}	9	**9**	48.00	LC50	Freitas and Rocha, 2011a
Daphnia magna	Water flea	Mg^{2+}	944	**2,755**	50.00	LC50	Dowden and Bennett, 1965
Daphnia magna	Water flea	Ca^{2+}	1,085	**1,920**	50.00	LC50	Dowden and Bennett, 1965

Table continued on next page.

Table B.1 (Continued)

Species	Common Name	Cation[a]	Cation Concentration (mg/l)	Chloride Concentration (mg/l)	Exposure Time (hours)	Response[b]	Reference[c]
Labeo rohita	Rohu carp (eggs)	Ca^{2+}	16	**29**	60.00	LC50	Mallick *et al.*, 2014
Labeo rohita	Rohu carp (eggs)	Ca^{2+}	3,644	**6,448**	72.00	LC50	Mallick *et al.*, 2014
Lithobates sylvatica[d]	Wood frog (tadpoles)	Mg^{2+}	1,848	**5,392**	72.00	LC50	Harless *et al.*, 2011
Pimephales promelas	Fathead minnow	Na^{+}	3,010	**4,640**	72.00	LC50	Adelman, *et al.*, 1976
Lithobates sylvatica[d]	Wood frog (tadpoles)	Na^{+}	3,006	**4,634**	72.00	LC50	Harless *et al.*, 2011
Anabolia nervosa	Brown sedge caddisfly	Na^{+}	2,759	**4,255**	72.00	LC50	Sutcliffe, 1961
Limnephilus stigma	Summer flier sedge caddisfy	Na^{+}	2,759	**4,255**	72.00	LC50	Sutcliffe, 1961
Labeo rohita	Rohu carp (fry)	Ca^{2+}	2,127	**3,763**	72.00	LC50	Mallick *et al.*, 2014
Ameletus sp.	Brown dun mayfly	Na^{+}	2,022	**3,118**	72.00	LC50	Echols *et al.*, 2009
Physa heterostropha	European physa snail	Na^{+}	1,924	**2,966**	72.00	LC50	Wurtz and Bridges, 1961
Lithobates sylvatica	Wood frog (tadpoles)	Ca^{2+}	1,509	**2,671**	72.00	LC50	Harless *et al.*, 2011
Lymnaea sp.	Pond snail (eggs)	Ca^{2+}	1,195	**2,113**	72.00	LC50	Dowden and Bennett, 1965
Lithobates sylvatica	Wood frog (Gosner stage 33 tadpoles)	Na^{+}	1,175	**1,812**	72.00	LC50	Copan, 2016
Lithobates sylvatica	Wood frog (Gosner stage 29 tadpoles)	Na^{+}	1,010	**1,558**	72.00	LC50	Copan, 2016
Labeo rohita	Rohu carp (spawn)	Ca^{2+}	845	**1,495**	72.00	LC50	Mallick *et al.*, 2014
Daphnia magna	Water flea	Ca^{2+}	274	**485**	72.00	LC50	Dowden and Bennett, 1965
Lymnaea sp.	Pond snail (eggs)	K^{+}	534	**484**	72.00	LC50	Dowden and Bennett, 1965
Lithobates sylvatica	Wood frog (Gosner stage 26 tadpoles)	Na^{+}	306	**472**	72.00	LC50	Copan, 2016
Lithobates sylvatica	Wood frog (Gosner stage 22 tadpoles)	Na^{+}	108	**116**	72.00	LC50	Copan, 2016
Lithobates sylvatica	Wood frog (Gosner stage 19 tadpoles)	Na^{+}	73	**112**	72.00	LC50	Copan, 2016
Daphnia magna	Water flea	K^{+}	61	**56**	72.00	LC50	Dowden and Bennett, 1965
Labeo rohita	Rohu carp (spawn)	Ca^{2+}	16	**27**	72.00	LC50	Mallick *et al.*, 2014
Anguilla rostrata	American eel (black eel stage)	Na^{+}	8,486	**13,085**	96.00	LC50	Hinton and Eversole, 1979
Oncorhynchus mykiss	Rainbow trout	Na^{+}	8,017	**12,371**	96.00	LC50	Vosyliene *et al.*, 2006
Gambusia affinis	Mosquito fish	Mg^{2+}	4,203	**12,260**	96.00	LC50	Wallen, *et al.*,1957
Anguilla rostrata	American eel (black eel stage)	Na^{+}	7,069	**10,900**	96.00	LC50	Hinton and Eversole, 1979
Gambusia affinis	Mosquito fish	Na^{+}	6,889	**10,622**	96.00	LC50	Wallen, *et al.*,1957
Gambusia affinis	Mosquito fish	Ca^{2+}	4,828	**8,542**	96.00	LC50	Wallen, *et al.*,1957
Hydropsyche betteni	Spotted sedge caddisfly	Na^{+}	5,235	**8,073**	96.00	LC50	Kundman, 1998
Lepomis macrochirus	Bluegill	Na^{+}	5,100	**7,864**	96.00	LC50	Trama, 1954
Lepomis macrochirus	Bluegill	Na^{+}	5,093	**7,853**	96.00	LC50	Patrick *et al.*, 1968
Lepomis macrochirus	Bluegill	Ca^{2+}	4,080	**7,220**	96.00	LC50	Cairns and Scheier, 1959
Lepomis macrochirus	Bluegill	Ca^{2+}	3,846	**6,804**	96.00	LC50	Trama, 1954; Patrick *et al.*, 1968
Oncorhynchus mykiss	Rainbow trout	Na^{+}	4,369	**6,743**	96.00	LC50	Spehar, 1987
Pimephales promelas	Fathead minnow	Na^{+}	4,261	**6,570**	96.00	LC50	Birge *et al.*, 1985

Table continued on next page.

Table B.1 (Continued)

Species	Common Name	Cation[a]	Cation Concentration (mg/l)	Chloride Concentration (mg/l)	Exposure Time (hours)	Response[b]	Reference[c]
Labeo rohita	Rohu carp (fingerlings)	Ca^{2+}	3,600	**6,300**	96.00	LC50	Mallick *et al.* 2014
Culex sp.	Mosquito	Na^{+}	4,032	**6,222**	96.00	LC50	Dowden and Bennett, 1965
Lepomis macrochirus	Bluegill	Ca^{2+}	3,430	**6,070**	96.00	LC50	Cairns and Scheier, 1959
Tubifex tubifex	Sludge Worm	Na^{+}	3,896	**6,008**	96.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Chironomus dilutus	Midge	Na^{+}	3,805	**5,867**	96.00	LC50	Elphick, *et al.*, 2011
Tubifex tubifex	Sludge Worm	Na^{+}	3,663	**5,648**	96.00	LC50	Elphick, *et al.*, 2011
Lepomis macrochirus	Bluegill	Na^{+}	3,787	**5,840**	96.00	LC50	Birge *et al.*, 1985
Eurycea bislineata	Northern two-lined salamander (larvae)	Na^{+}	3,570	**5,505**	96.00	LC50	Jones, *et al.*, 2015
Hydropsyche sp.	Spotted sedge caddisfly	Na^{+}	3,541	**5,459**	96.00	LC50	Roback, 1965
Lithobates sylvatica[d]	Wood frog (tadpoles)	Mg^{2+}	1,815	**5,295**	96.00	LC50	Harless, *et al.*, 2011
Gammarus pseudolimnaeus	Scud	Na^{+}	3,030	**4,670**	96.00	LC50	Blasius and Merritt, 2002
Pimephales promelas	Fathead minnow	Na^{+}	3,022	**4,659**	96.00	LC50	Wisconsin State Laboratory of Health, 1998
Pimephales promelas	Fathead minnow	Na^{+}	3,010	**4,640**	96.00	LC50	Adelman *et al.*, 1976
Lithobates sylvatica[d]	Wood frog (tadpoles)	Na^{+}	2,974	**4,659**	96.00	LC50	Harless, *et al.*, 2011
Carassius auratus	Goldfish	Na^{+}	2,888	**4,453**	96.00	LC50	Adelman *et al.*, 1976
Tubifex tubifex	Sludge worm	Na^{+}	2,774	**4,278**	96.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Microhyla ornata	Ornate narrow-mouthed frog (hind-limb tadpoles)	Na^{+}	2,774	**4,278**	96.00	LC50	Padhye and Ghate, 1992
Anabolia nervosa	Brown sedge caddisfly	Na^{+}	2,759	**4,255**	96.00	LC50	Sutcliffe, 1961
Limnephilus stigma	Summer flier sedge caddisfly	Na^{+}	2,759	**4,255**	96.00	LC50	Sutcliffe, 1961
Pimephales promelas	Fathead minnow	Na^{+}	2,645	**4,079**	96.00	LC50	Elphick, *et al.*, 2011
Labeo rohita	Rohu carp (fry)	Ca^{2+}	2,301	**4,072**	96.00	LC50	Mallick *et al.*, 2014
Daphnia magna	Water flea	Na^{+}	2,638	**4,071**	96.00	LC50	Wisconsin State Laboratory of Health, 1998
Chironomus attenuatus	Midge	Na^{+}	2,611	**4,026**	96.00	LC50 at 18°C	Thornton and Sauer, 1972
Hyalella azeteca	Amphipod	Na^{+}	2,560	**3,947**	96.00	LC50	Lasier *et al.*, 1997
Bufo americanus	American toad (tadpoles)	Na^{+}	2,547	**3,928**	96.00	LC50	Collins and Russell, 2009
Pimephales promelas	Fathead minnow	Na^{+}	2,514	**3,876**	96.00	LC50	Mount *et al.*, 1997
Hexagenia limbata	Giant burrowing mayfly	Na^{+}	2,478	**3,822**	96.00	LC50	Chadwick, 2001
Daphnia magna	Water flea	Na^{+}	2,373	**3,658**	96.00	LC50	Cowgill and Milazzo, 1990
Lepidostoma sp.	Little brown sedge caddisfly	Na^{+}	2,360	**3,640**	96.00	LC50	Williams *et al.*, 1999
Corbicula fluminea	Freshwater golden clam	Ca^{2+}	2,009	**3,554**	96.00	LC50	Coldsnow and Relyea, 2018
Hydroptila angusta	Varicolored microcaddisfly	Na^{+}	2,174	**3,352**	96.00	LC50	Hamilton *et al.*, 1975

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Table B.1 (Continued)

Species	Common Name	Cation[a]	Cation Concentration (mg/l)	Chloride Concentration (mg/l)	Exposure Time (hours)	Response[b]	Reference[c]
Villosa delumbis	Easter creekshell mussel (juveniles)	Na^+	2,057	**3,173**	96.00	EC50	Bringolf, *et al.*, 2007
Cricotopus trifascia	Midge	Na^+	2,043	**3,149**	96.00	LC50	Hamilton *et al.*, 1975
Rana clamitans	Green frog (tadpoles)	Na^+	2,016	**3,109**	96.00	LC50	Collins and Russell, 2009
Lumbriculus variegatus	California blackworm	Na^+	2,010	**3,100**	96.00	LC50	Elphick, *et al.*, 2011
Lithobates sylvatica[d]	Wood frog (tadpoles)	Na^+	2,010	**3,099**	96.00	LC50	Sanzo and Hecnar, 2006
Gyraulus parvus	Planorbid snail	Na^+	1,996	**3,078**	96.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Microhyla ornata	Ornate narrow-mouthed frog (8-day embryos)	Na^+	1,978	**3,049**	96.00	LC50	Padhye and Ghate, 1992
Cirrhinius mrigalo	Mrigal carp (fry)	Na^+	1,959	**3,021**	96.00	LC50	Ghosh and Pal, 1969
Labeo rohoto	Rohu carp (fry)	Na^+	1,959	**3,021**	96.00	LC50	Ghosh and Pal, 1969
Catla catla	Major (Indian) carp (fry}	Na^+	1,959	**3,021**	96.00	LC50	Ghosh and Pal, 1969
Gyraulus parvus	Planorbid snail	Na^+	1,951	**3,009**	96.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Lirceus fontinalis	Isopod	Na^+	1,926	**2,970**	96.00	LC50	Birge *et al.*, 1985
Pimephales promelas	Fathead minnow	Ca^{2+}	1,672	**2,958**	96.00	LC50	Mount *et al.*, 1997
Physa heterostropha	European physa snail	Na^+	1,857	**2,863**	96.00	LC50	Wurtz and Bridges, 1961
Pseudacris crucifer	Spring peeper (tadpoles)	Na^+	1,835	**2,830**	96.00	LC50	Collins and Russell, 2009
Lampsilis siliquoidea	Fat mucket mussel (juveniles)	Na^+	1,794	**2,766**	96.00	EC50	Bringolf, *et al.*, 2007
Lithobates sylvatica[d]	Wood frog (tadpoles)	Ca^{2+}	1,437	**2,543**	96.00	LC50	Harless *et al.*, 2011
Ameletus sp.	Brown dun mayfly	Na^+	1,625	**2,505**	96.00	LC50	Echols *et al.*, 2009
Physa gyrina	Tadpole physa snail	Na^+	1,608	**2,480**	96.00	LC50	Birge *et al.*, 1985
Lithobates clamitans	Green frog (tadpoles)	Na^+	1,570	**2,421**	96.00	LC50	Jones *et al.*, 2015
Lampsilis fasciola	Wavy-rayed lampmussel	Na^+	1,566	**2,414**	96.00	EC50	Bringolf, *et al.*, 2007
Daphnia magna	Water flea	Na^+	1,549	**2,390**	96.00	LC50	Arambasic *et al.*, 1995
Corbicula fluminea	Freshwater golden clam	Mg^{2+}	712	**2,162**	96.00	LC50	Coldsnow and Relyea, 2018
Pycnopsyche guttifer	Great autumn brown sedge caddisfly	Na^+	1,386	**2,140**	96.00	LC50	Blasius and Merritt, 2002
Pycnopsyche lepida	Northern caddisfly	Na^+	1,386	**2,140**	96.00	LC50	Blasius and Merritt, 2002
Musculium transverum	Long fingernail clam	Na^+	1,252	**1,930**	96.00	LC50	Soucek *et al.*, 2011
Isonychia bicolor	Mahogany dun mayfly	Na^+	1,220	**1,880**	96.00	LC50	Echols *et al.*, 2009
Daphnia magna	Water flea	Na^+	1,201	**1,853**	96.00	LC50	Anderson, 1950
Lithobates sylvatica[d]	Wood frog (tadpoles)	Na^+	1,116	**1,721**	96.00	LC50	Collins and Russell, 2009
Microhyla ornata	Ornate narrow-mouthed frog (late gastrula)	Na^+	1,067	**1,644**	96.00	LC50	Padhye and Ghate, 1992
Lymnaea sp.	Pond snail (eggs)	Ca^{2+}	929	**1,644**	96.00	LC50	Dowden and Bennett, 1965
Lithobates sylvatica	Wood frog (Gosner stage 33 tadpoles)	Na^+	1,066	**1,643**	96.00	LC50	Copan, 2016
Lithobates sylvatica[d]	Wood frog (tadpoles)	Na^+	1,037	**1,599**	96.00	LC50	Sanzo and Hecnar, 2006

Table continued on next page.

Table B.1 (Continued)

Species	Common Name	Cation[a]	Cation Concentration (mg/l)	Chloride Concentration (mg/l)	Exposure Time (hours)	Response[b]	Reference[c]
Ceriodaphnia dubia	Water flea	Na^+	1,035	**1,596**	96.00	LC50	Wisconsin State Laboratory of Health, 1998
Lampsilis siliquoidea	Fat mucket mussel (juveniles)	Na^+	1,035	**1,595**	96.00	LC50	Hazelton *et al.*, 2013
Pimephales promelas	Fathead minnow	Mg^{2+}	541	**1,579**	96.00	LC50	Mount *et al.*, 1997
Ligumia recta	Black sandshell mussel (juveniles)	Na^+	987	**1,523**	96.00	LC50	Hazelton *et al.*, 2013
Lithobates clamitans	Wood frog (Gosner stage 29 tadpoles)	Na^+	977	**1,507**	96.00	LC50	Copan, 2016
Daphnia pulex	Water flea	Na^+	952	**1,470**	96.00	LC50	Birge *et al.*, 1985
Hexagenia limbata	Giant burrowing mayfly	Na^+	944	**1,456**	96.00	LC50 at 28°C	Chadwick, 2001
Lithobates sylvatica	Wood frog (Gosner stage 33 tadpoles)	Na^+	912	**1,407**	96.00	LC50	Copan, 2016
Ceriodaphnia dubia	Water flea	Na^+	908	**1,400**	96.00	LC50	Cowgill and Milazzo, 1990
Daphnia carinata	Water flea	Na^+	908	**1,400**	96.00	LC50	Hall and Burns, 2002
Hyalella azteca	Amphipod	Na^+	896	**1,382**	96.00	LC50	Elphick, *et al.*, 2011
Lithobates sylvatica	Wood frog (Gosner stage 29 tadpoles)	Na^+	871	**1,343**	96.00	LC50	Copan, 2016
Microhyla ornata	Ornated narrow-mouthed frog (hind-limb tadpoles)	K^+	1,332	**1,207**	96.00	LC50	Padhye and Ghate, 1992
Tubifex tubifex	Sludge worm	Na^+	781	**1,204**	96.00	EC50	Khangarot, 1991
Ambystoma maculatum	Spotted salamander (tadpoles)	Na^+	764	**1,178**	96.00	LC50	Collins and Russell, 2009
Sphaerium simile	Fingernail clam (juveniles)	Na^+	713	**1,100**	96.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Daphnia carinata	Water flea	Na^+	689	**1,062**	96.00	LC50	Hall and Burns, 2002
Neocloeon triangulifer	Triangle small minnow mayfly	Na^+	689	**1,062**	96.00	LC50	Soucek and Dickenson, 2015
Lithobates sylvatica	Wood frog (Gosner stage 19 tadpoles)	Na^+	630	**972**	96.00	LC50	Copan, 2016
Lepomis macrochirus	Bluegill	K^+	1,054	**956**	96.00	LC50	Trama, 1954; Patrick *et al.*, 1968
Tubifex tubifex	Sludge worm	K^+	912	**827**	96.00	EC50	Khangarot, 1991
Labeo rohita	Rohu carp (spawn)	Ca^{2+}	454	**804**	96.00	LC50	Mallick *et al.*, 2014
Microhyla ornata	Ornate narrow-mouthed frog (8-day tadpoles)	K^+	836	**757**	96.00	LC50	Padhye and Ghate, 1992
Sphaerium simile	Fingernail clam (juveniles)	Na^+	480	**740**	96.00	LC50	GLEC and INHS, 2008; Soucek *et al.*, 2011
Microhyla ornata	Ornate narrow-mouthed frog (late gastrula)	K^+	742	**672**	96.00	LC50	Padhye and Ghate, 1992
Lithobates sylvatica	Wood frog (Gosner stage 26 tadpoles)	Na^+	387	**596**	96.00	LC50	Copan, 2016
Lymnaea sp.	Pond snail (eggs)	K^+	577	**523**	96.00	LC50	Dowden and Bennett, 1965
Tubifex tubifex	Sludge worm	Ca^{2+}	281	**497**	96.00	EC50	Khangarot, 1991
Bufo boreas	Boreal toad	Mg^{2+}	165	**483**	96.00	EC50	Lewis, 1999
Physa heterosperna	European physa snail	K^+	447	**447**	96.00	LC50	Patrick *et al.*, 1968
Gambusia affins	Mosquito fish	K^+	481	**437**	96.00	LC50	Wallen *et al.*, 1957

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Table B.1 (Continued)

Species	Common Name	Cation[a]	Cation Concentration (mg/l)	Chloride Concentration (mg/l)	Exposure Time (hours)	Response[b]	Reference[c]
Pimephales promelas	Fathead minnow	K^+	462	**418**	96.00	LC50	Mount *et al.*, 1997
Callibaetis coloradensis	Gray quill mayfly	Na^+	275	**425**	96.00	LC50	Wichard, 1975
Lithobates sylvatica	Wood frog (Gosner stage 26 tadpoles)	Na^+	273	**421**	96.00	LC50	Copan, 2016
Lithobates sylvatica	Wood frog (Gosner stage 22 tadpoles)	Na^+	141	**217**	96.00	LC50	Copan, 2016
Lithobates sylvatica	Wood frog (Gosner stage 22 tadpoles)	Na^+	86	**133**	96.00	LC50	Copan, 2016
Lithobates sylvatica	Wood frog (Gosner stage 19 tadpoles)	Na^+	79	**122**	96.00	LC50	Copan, 2016
Lithobates sylvatica	Wood frog (Gosner stage 19 tadpoles)	Na^+	63	**97**	96.00	LC50	Copan, 2016
Lithobates sylvatica	Wood frog (Gosner stage 19 tadpoles)	Na^+	56	**86**	96.00	LC50	Copan, 2016
Daphnia magna	Water flea	K^+	15	**14**	96.00	LC50	Dowden and Bennett, 1965
Labeo rohita	Rohu carp (eggs)	Ca^{2+}	10	**19**	96.00	LC50	Mallick *et al.*, 2014
Daphnia magna	Water flea	Mg^{2+}	889	**2,595**	100.00	LC50	Dowden and Bennett, 1965
Daphnia magna	Water flea	Na^+	1,225	**1,889**	100.00	LC50	Dowden and Bennett, 1965
Daphnia magna	Water flea	Ca^{2+}	649	**415**	100.00	LC50	Dowden and Bennett, 1965
Daphnia magna	Water flea	K^+	356	**323**	100.00	LC50	Dowden and Bennett, 1965
Nitzschia linearis	Pennate diatom	Ca^{2+}	1,130	**2,000**	120.00	LC50	Patrick, *et al.*, 1968
Nitzschia linearis	Pennate diatom	Na^+	956	**1,474**	120.00	LC50	Patrick, *et al.*, 1968
Nitzschia linearis	Pennate diatom	K+	701	**636**	120.00	LC50	Patrick, *et al.*, 1968
Isonychia bicolor	Mahogany dun mayfly	Na^+	681	**1,049**	168.00	LC50	Echols *et al.*, 2009
Corbicula fluminea	Freshwater golden clam	Na^+	6,530	**10,069**	192.00	LC50	Coldsnow and Relyea, 2018
Corbicula fluminea	Freshwater golden clam	Ca^{2+}	1,130	**2,235**	192.00	LC50	Coldsnow and Relyea, 2018
Corbicula fluminea	Freshwater golden clam	Mg^{2+}	583	**1,769**	192.00	LC50	Coldsnow and Relyea, 2018
Aedes stritatus	Floodwater mosquito (larvae)	Na^+	1,784	**2,752**	194.00	LC50	Kardatzke, 1980
Aedes cinereus	Ashy mosquito (larvae)	Na^+	1,346	**2,076**	230.00	LC50	Kardatzke, 1980
Aedes communis	Woodland snow pool mosquito (larvae)	Na^+	574	**884**	278.00	LC50	Kardatzke, 1980
Aedes provocans	Provoking mosquito (larvae)	Na^+	517	**798**	278.00	LC50	Kardatzke, 1980
Aedes punctor	Puncturing mosquito (larvae)	Na^+	1,416	**2,184**	281.00	LC50	Kardatzke, 1980
Aedes stimulans	Woodland mosquito (larvae)	Na^+	1,606	**2,477**	290.00	LC50	Kardatzke, 1980
Aedes canadensis	Woodland pool mosquito (larvae)	Na^+	1,785	**2,753**	293.00	LC50	Kardatzke, 1980
Aedes abserratus	Serrated mosquito (larvae)	Na^+	1,231	**1,899**	298.00	LC50	Kardatzke, 1980
Aedes fitchii	Fitch's ditch mosquito (larvae)	Na^+	1,180	**1,820**	322.00	LC50	Kardatzke, 1980
Aedes diantaeus	Long-antennaed mosquito (larvae)	Na^+	1,231	**1,899**	456.00	LC50	Kardatzke, 1980

Table continued on next page.

Table B.1 (Continued)

[a] *Cations include calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+).*

[b] *LC50 is the concentration that is lethal to 50 percent of the test organisms over the test period. EC50 is the concentration at which 50 percent of the test organisms showed a toxicity effect. Mortality was the effect for the EC50s reported in this table. Higher LC50 and EC50 values means lower toxicity of the chemical to the organism.*

[c] *References are listed in Appendix B.*

[d] *Reported as* Rana sylvatica. *This species has since been reclassified as* Lithobates sylvatica.

[e] *Reported as* Stenonema rubrum. *This species has since been reclassified as* Maccaffertium modestum.

Source: SEWRPC

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RELATIVE SALT (NACL) TOLERANCE OF SELECTED PLANTS

APPENDIX C

Table C.1
Relative Salt (NaCl) Tolerance of Selected Plants

Common Name	Scientific Name	Tolerance
	Deciduous Trees	
Alder, European black	*Alnus glutinosa*	L-M
Alder, speckled	*Alnus rugosa*	L-M
Alder, white	*Alnus incana*	L
Apricot	*Prunus armeniaca*	H
Ash, blue	*Fraxinus quadrangulata*	M
Ash, European	*Fraxinus excelsior*	H
Ash, green	*Fraxinus pennsylvanica*	M-H
Ash, white	*Fraxinus americana*	L-H
Aspen, bigtooth	*Populus grandidentata*	M-H
Aspen, upright European	*Populus tremula*	H
Aspen, quaking	*Populus tremuloides*	L-H
Beech, American	*Fagus grandifolia*	L-M
Beech, European	*Fagus sylvatica*	L
Birch, Cherry	*Betula, lenta*	H
Birch, Dahurian	*Betula davurica*	L
Birch, European white	*Betula pendula*	M
Birch, gray	*Betula populifolia*	M-H
Birch, Japanese whitespire	*Betula platyphylla*	L-M
Birch, paper	*Betula papyrifera*	L-H
Birch, river	*Betula nigra*	M
Birch, yellow	*Betula alleghaniensis*	M
Box-elder	*Acer negundo*	L-M
Buckeye, Ohio	*Aesculus glabra*	M
Buckeye, yellow	*Aesculus octandra*[a]	M
Buckthorn, common	*Rhamnus cathartica*	H
Butternut	*Juglans cinerea*	H
Catalpa, northern	*Catalpa speciosa*	M-:H
Catalpa, southern	*Catalpa bignonioides*	M
Cherry, Amur choke	*Prunus maackii*	M
Cherry, black	*Prunus serotina*	L-H
Cherry, European bird	*Prunus padus*	M-H
Cherry, choke	*Prunus virginana*	M-H
Cherry, Mazzard	*Prunus avium*	M
Cherry, pin	*Prunus pennsylvanica*	M
Cherry, sargent	*Prunus sargentii*	M
Chestnut, American	*Castanea dentata*	M
Coffeetree, Kentucky	*Gymnocladus dioicus*	M-H
Cork tree, Amur	*Phellodendron amurense*	M
Cottonwood, eastern	*Populus deltoides*	L-H
Crabapple, Siberian	*Malus baccata*	M
Cypress, bald	*Taxodium distichum*	H
Dogwood, flowering	*Cornus florida*	M
Elm, American	*Ulmus americana*	L-H
Elm, Chinese	*Ulmus parvifolia*	M
Elm, red	*Ulmus rubra*	M
Elm, Scotch	*Ulmu glabra*	M-H
Elm, Siberian	*Ulmus pumila*	H
Elm, smoothleaf	*Ulmus carpinifolia*	L-H
False-cypress, Sawara	*Chamaecyparis pisifera*	L
Filbert, European	*Corylus avellana*	L
Filbert, Turkish	*Corylus colurna*	L
Ginko	*Ginko biloba*	M
Hackberry, common	*Celtis occidentalis*	L-M

Table continued on next page.

Table C.1 (Continued)

Common Name	Scientific Name	Tolerance
	Deciduous Trees (continued)	
Hackberry, sugar	*Celtis laevigata*	L
Hawthorn, cockspur	*Crataegus crus-galli*	L-H
Hawthorn, downy	*Crataegus mollis*	L
Hawthorn, green[b]	*Crataegus viridis*	L
Hawthorn, Washington	*Crataegus phaenopyrum*	L
Hickory, bitternut	*Carya cordiformis*	M-H
Hickory, pignut	*Carya glabra*	L-H
Hickory, shagbark	*Carya ovata*	L-H
Honey locust, thornless	*Gleditsia triacanthos*	L-H
Hornbeam, American	*Carpinus caroliniana*	L
Hornbeam, European	*Carpinus betulus*	L
Horse chestnut, common	*Aesculus hippocastanum*	M-H
Ironwood	*Ostrya virginiana*	M
Katsura tree	*Cercidiphyllum japonicum*	M
Larch, American	*Larix laricina*	L
Larch, European	*Larix decidua*	H
Larch, Japanese	*Larix kaempferi*	H
Lilac, Peking	*Syringa pekinensis*	H
Linden, American	*Tilia americana*	L-H
Linden, Crimean	*Tilia X euchlora*	L
Linden, large-leaved	*Tilia platyphyllos*	H
Linden, little-leaf	*Tilia cordata*	L-H
Locust, black	*Robina pseudoacacia*	H
Magnolia, cucumber tree	*Magnolia acuminata*	M
Magnolia saucer	*Magnolia X soulangiana*	M
Maple, Amur	*Acer ginnala*	M
Maple, black	*Acer nigrum*[c]	L-M
Maple, box elder	*Acer negundo*	M
Maple, Freeman's	*Acer X freemanii*	M
Maple, hedge	*Acer campestre*	M-H
Maple, Miyabe's	*Acer miyabei*	M-H
Maple, Norway	*Acer platanoides*	H
Maple, paperbark	*Acer griseum*	M
Maple, purpleblow	*Acer truncatum*	M
Maple, red	*Acer rubrum*	L-M
Maple, silver	*Acer saccharinum*	L-H
Maple, sugar	*Acer saccharum*	L
Maple, sycamore	*Acer pseudoplatanus*	L-H
Mountain-ash, American	*Sorbus americana*	M
Mountain-ash, European	*Sorbus aucuparia*	L-M
Mulberry, red	*Morus rubra*	H
Mulberry, white	*Morus alba*	H
Oak, black	*Quercus velutina*	M
Oak, bur	*Quercus macrocarpa*	M-H
Oak, Chinkapin	*Quercus muehlenbergii*	L-M
Oak, English	*Quercus robur*	L-H
Oak, Hill's	*Quercus ellipsoidalis*	M
Oak, pin	*Quercus palustris*	L
Oak, post	*Quercus sellata*	M
Oak, red	*Quercus rubra*	L-H
Oak, scarlet	*Quercus coccinea*	L
Oak, shingle	*Quercus imbricaria*	M
Oak, swamp white	*Quercus bicolor*	L-M
Oak, white	*Quercus alba*	L-H

Table continued on next page.

Table C.1 (Continued)

Common Name	Scientific Name	Tolerance
Deciduous Trees (continued)		
Pagoda tree, Japanese	*Sophora japonica*[e]	L-H
Pawpaw	*Asimina triloba*	M
Peach	*Prunus persica*	L
Pear, Callery	*Pyrus calleryana*	M
Pecan	*Carya illinoiensis*	M
Persimmon common	*Diospyros virginiana*	M
Plum, wild	*Prunus americana*	M-H
Poplar, big-tooth aspen	*Populus grandidentata*	H
Poplar, black	*Populus nigra*	H
Poplar, gray	*Populus canescens*	H
Poplar, laurel	*Populus laurifolia*	L
Poplar, white	*Populus alba*	H
Raintree, golden	*Koelreuteria paniculata*	M
Redwood, dawn	*Metasequoia glyptostroboides*	L
Sassafras, common	*Sassafras albidum*	M
Spindletree, European	*Euonymus europaea*	L-H
Sweetgum, American	*Liquidambar styraciflua*	M-H
Sycamore	*Platanus orientalis*	L-M
Tree of Heaven	*Ailanthus altissima*	H
Tulip tree	*Liriodendron tulipifera*	L
Tupelo, black	*Nyssa sylvatica*	M
Walnut, black	*Juglans nigra*	M-H
Walnut, English	*Juglans regia*	M
Willow, black	*Salix nigra*	M-H
Willow, corkscrew	*Salix matsudana*	H
Willow, crack	*Salix fragilis*	L
Willow, weeping	*Salix alba*	L-H
Yellow wood	*Cladrastis lutea*	M
Deciduous Shrubs		
Barberry, Japanese	*Berberis thunbergii*	H
Barberry, Korean	*Berberis koreana*	H
Bayberry, northern	*Morella pennsylvanica*	M-H
Bearberry	*Arctostaphylos uva-ursi*	H
Beauty bush	*Kolkwitzia amabilis*	L
Boxwood, common	*Buxus sempervirens*	L
Buffalo berry	*Shepherdia argentea*	M-H
Burning bush	*Euonymus alatus*	H
Butterfly bush	*Buddleja davidii*	H
Chastetree	*Vitex agnus-castus*	H
Chokeberry, black	*Aronia melanocarpa*	M
Chokeberry, red	*Aronia arbutifolia*	M
Clethra, summersweet	*Clethra alnifolia*	M
Corralberry	*Symphoricarbos arbiculatus*	L
Cotoneaster, cranberry	*Cotoneaster apiculatus*	M
Cotoneaster, hedge	*Cotoneaster acutifolius*	M
Cotoneaster, many-flowered	*Cotoneaster multiflorus*	M
Cotoneaster, rockspray	*Cotoneaster horizontalis*	M
Cotoneaster, spreading	*Cotoneaster divaricatus*	M
Currant, alpine	*Ribes alpinum*	H
Currant, black	*Ribes nigrum*	M-H
Currant, clove	*Ribes odoratum*	H
Dogwood, correlianchery	*Cornus mas*	L
Dogwood, pagoda	*Cornus alternifolia*	M
Dogwood, gray	*Cornus racemosa*	L

Table continued on next page.

Table C.1 (Continued)

Common Name	Scientific Name	Tolerance
	Deciduous Shrubs (continued)	
Dogwood, red osier	*Cornus sericea*	L
Dogwood, Siberian	*Cornus alba*	L
Firethorn, scarlet	*Pyracantha coccinea*	H
Forsythia	*Forsythia X intermedia*	M
Fuchsia	*Fuchsia hybrida*	S
Hawthorn, English	*Crataegus levigata*	L
Hawthorn, dotted	*Crataegus punctata*	L
Hydrangea, bigleaf	*Hydrangea macrophylla*	H
Indigo-bush	*Amorpha fruticosa*	H
Jetbead, black	*Rhodotypos scandens*	H
Juneberry	*Amelanchier canadensis*	M
Lilac, common	*Syringa vulgaris*	L-H
Lilac, Japanese tree	*Syringa reticulata*	M
Lilac, Miss Kim	*Syringa pubescens*	M
Lilac, Palibin	*Syringa meyeri*	M
Locust, bristly	*Robinia hispida*	H
Maple, Amur	*Acer ginnala*	L-M
Maple, Japanese	*Acer palmatum*	M
Maple, Tatarian	*Acer tataricum*	L
Mockorange	*Philadelphys coronarius*	M
Mountain-ash, showy	*Sorbus decora*	H
Ninebark, dwarf eastern	*Physocarpus opulifolius*	L-M
Osage-orange	*Maclura pomifera*	M
Pea-shrub, Siberian	*Caragana arborescens*	H
Plum, beach	*Prunus maritima*	H
Potentilla	*Dasiphora fruticosa*	H
Privet, common	*Ligustrum vulgare*	L-M
Quince, flowering	*Chaenomeles speciosa*	L-M
Redbud	*Cercis canadensiss*	L
Rose, dog	*Rosa canina*	L
Rose, rugosa	*Rosa rugosa*	L-H
Rose, Virginia	*Rosa virginiana*	L-H
Russian olive	*Elaeagnus angustifolia*	H
Sage, Russian	*Perovskia atriplicifolia*	H
Salt tree	*Halimodendron halodendron*	H
Sandcherry, eastern	*Prunus pumila*	H
Serviceberry, apple	*Amelanchier X grandiflora*	L-H
Serviceberry, shadblow	*Amelanchier arborea*	M
Serviceberry, Allegheny	*Amelanchier laevis*	M
Shrub bush clover	*Lespedeza bicolor*	H
Skunkbush	*Rhus trilobata*	H
Snowberry	*Symphoricarpos albus*	M-H
Spiraea, Japanese	*Spiraea japonica*	M
Spiraea, snowmound	*Spiraea nipponica*	M
Spiraea, Vanhoutte	*Spiraea X vanhouttei*	
Sprite	*Hippophae rhamnoides*	H
St. Johnswort, Kalm's	*Hypericum kalmianum*	H
Sumac, fragrant	*Rhus aromatica*	H
Sumac, smooth	*Rhus glabra*	M-H
Sumac, staghorn	*Rhyus typhina*	H
Sumac, winged	*Rhus copallina*	H
Sweet-fern	*Comptonia peregrina*	H
Tamarisk	*Tamarix chinensis*	H
Virburnum, Arrowwood	*Vibrunum dentatum*	M

Table continued on next page.

Table C.1 (Continued)

Common Name	Scientific Name	Tolerance
	Deciduous Shrubs (continued)	
Virburnum, American cranberrybush	*Viburnum opuulus*	M
Viburnum, blackhaw	*Viburnum prunifolium*	M
Virburnum, Nannyberry	*Viburnum lentago*	M
Viburnum, Siebold	*Viburnum sieboldii*	M
Willow, goat	*Salix caprea*	M-H
Willow, laurel	*Salix pentandra*	M
Willow, purple	*Salix purpurea*	M-H
Willow, pussy	*Salix discolor*	H
Winterberry	*Ilex verticillata*	M
Yucca, Adam's needle	*Yucca filamentosa*	H
Yucca, golden sword	*Yucca filifera*	H
	Evergreen Trees and Shrubs	
Arborvitae	*Thuja occindentalis*	L-H
Camellia	*Camellia japonica*	L
Fir, balsam	*Abies balsamea*	L-M
Fir, white	*Albes concolor*	M-H
Fir, Douglas	*Pseudotsuga menziesii*	L-M
Firethorn, scarlet	*Pyracantha coccinea*	L-M
Gardenia	*Gardenia augusta*	S
Golden Marguerite	*Euryops pectinatus*	L
Hemlock, Canadian	*Tsuga canadensis*	L
Hibiscus, Chinese	*Hibiscus rosa-sinensis*	L
Juniper, Chinese	*Juniperus chinensis*	M
Juniper, common	*Juniperus communis*	H
Juniper, creeping	*Juniperus horizontalis*	H
Juniper, eastern	*Juniperus virginiana*	H
Juniper, Pfitzer	*Juniperus X pfitzeriana*	H
Juniper, Rocky Mountain	*Juniper scopulorum*	H
Pine, Bosnian	*Pinus leucodrmis*	H
Pine, European black	*Pinus nigra*	M-H
Pine, eastern white	*Pinus strobus*	L
Pine, jack	*Pinus bankisana*	H
Pine, Japanese black	*Pinus thunbergiana*	H
Pine, Japanese white	*Pinus parviflora*	H
Pine, Mugho	*Pinus mugo*	H
Pine, ponderosa	*Pinus ponderosa*	M-H
Pine, red	*Pinus resinosa*	L
Pine, Scots	*Pinus sylvestris*	L-H
Pine, Swiss stone	*Oinus cembra*	L
Red-cedar, eastern	*Juniperus virginiana*	M-H
Redwood, dawn	*Metasequioa glyptostroboides*	L
Sea-buckthorn	*Hippophae rhamnoides*	M-H
Spruce, blue	*Picea pungens*	L-H
Spruce, Norway	*Picea abies*	L-M
Spruce, white	*Picea glauca*[d]	L-H
Wintercreeper, purpleleaf	*Euonymus fortunei*	H
Yew, English	*Taxus baccata*	L
Yew, Japanese	*Taxus cuspidata*	L-H
	Grasses	
Bluegrass, Kentucky	*Poa pratensis*	L
Bluestem, little	*Schizachyrium scoparium*	M
Feather reed grass	*Calamagrostis X acutiflora*	H
Fescue, Elijah Blue	*Festuca glauca*	M
Fescue, red	*Festuca rubra*	M

Table continued on next page.

Table C.1 (Continued)

Common Name	Scientific Name	Tolerance
	Grasses (continued)	
Fescue, tall (Kentucky 31)	*Festuca arundinacea*	H
Fountain grass	*Pennisetum alopecuroides*	H
Lyme grass, blue	*Leymus arenarius*	H
Maiden grass	*Miscanthus* spp.	M
Oats, northern sea	*Chasmantium latifolium*	H
Oat grass, blue	*Helictotrichon sempervirens*	M
Switch grass	*Panicum virgatum*	H
Turf lily, giant	*Ophiopogon jaburan*	M
	Forbs	
Ageratum	*Ageratum houstonianum*	M
Alyssum, sweet	*Lobularia maritima*	M
Amaranth, globe	*Gomphrena globosa*	M
Amaryllis	*Hippeastrum hybridum*	L
Anthemis	*Anthemis punctata*	H
Anthurium	*Anthruium andreanum*	L
Artemisia, dwarf silvermound	*Artemisia schmidtiana*	M
Aster, China	*Callistephus chinensis*	M
Aster, purple dome	*Aster navae-angliae*	M
Aster, seaside	*Erigeron gaucus*	H
Baby's-breath	*Gypsophila paniculata*	M
Baby's-breath	*Gypsophila vaniculata*	M
Beardtongue	*Penstemon* spp.	M
Begonia	*Begonia bunchii*	L
Begonia	*Begonia ricinifolia*	L
Begonia, Rex	*Begonia Rex-cultorum*	S
Bergenia, heart-leaf	*Bergenia cordifolia*	M
Bouvardia	*Vouvardia longiflora*	M
Cactus, apple	*Cereus peruviana*	M
Carnation	*Dianthus caryophyllus*	M
Catmint	*Nepeta X faassenii*	M
Celosia, chief	*Celosia argental cristata*	H
Cinquefoil, Jackman Shrubby	*Potentilla fruticosa*	H
Clematis	*Clematis orientalis*	H
Coleus	*Coleus blumei*	H
Coral bells, chatterbox	*Heuchera sanguinea*	M
Coral bells, purple palace	*Heuchera micrantha*	M
Cosmos	*Cosmos bipinnatus*	L
Coxcomb, crested	*Celosia argenta cristata*	M
Creeping lilyturf	*Liriope spicata*	M
Cucumber leaf	*Helianthus debilis*	H
Cupid's dart	*Catananche caerulea*	M
Cyclamen, Persian	*Cyclamen persicum*	L
Daisy, Becky shasta	*Leucanthemum X superbum*	M
Daisy, gerbera	*Gerbera jamesonii*	M
Daylily	*Hemerocallis* spp.	M
Dusty miller	*Artemesia stelleran*	M
Evergreen candytuft	*Iberis sempervirens*	M
Felicia, blue	*Felicia amelloides*	L
Gazania	*Gazania aurantiacum*	M
Gentian, prairie	*Eustoma grandiforum*	M
Geranium	*Pelargonium X horticum*	L
Geranium	*Pelargonium domesticum*	H
Geranium, ivy	*Pelargonium peltatum*	M
Gladiola	*Gladiolus* spp.	L

Table continued on next page.

Table C.1 (Continued)

Common Name	Scientific Name	Tolerance
	Forbs (continued)	
Goblin blanket flower	*Gaillardia X grandiflora*	M
Hen and chicks	*Sempervivum* spp.	M
Holly, sea	*Eryngium X oliverianum*	H
Holly, sea	*Eryngium X tripartitum*	H
Hosta, fragrant	*Hosta plantaginea*	M
Hosta, variegated	*Hosta undulata*	M
Impatiens	*Impatiens X hawkeri*	L
Iris, bearded	*Iris* spp.	M
Iris, Siberian	*Iris sibirica*	M
Ivy, English	*Hedera helix*	H
Jade plant	*Crassula ovata*	M
Kalanchoe	*Kalanchoe* spp.	M
Larkspur	*Consolida ambigua*	L
Lavender, purple sea	*Limonium latifolium*	M-H
Lily	*Lilium* spp.	L
Lily of the Nile	*Agapanthus orientalis*	L
Lily, spider	*Hymenocallis keyensis*	M
Love-lies-bleeding	*Amaranthus tricolor*	H
Mallow, prairie	*Sidalcea malviflora*	M
Marigold, Aztec	*Tagetes erecta*	M
Marigold, French	*Tagetes patula*	M
Marigold, pot	*Calendula officinalis*	M
Mum	*Chrysanthemum morifolium*	M
Myrtle	*Vinca minor*	L
Narcissus, paperwhite	*Narcissus tazetta*	L
Nasturtium	*Tropaeolum majus*	M
Obedient plant	*{hysostegia virginiana*	M
Onion, ornamental	*Allium senescens*	H
Pansy	*Viola X wittrockiana*	L
Periwinkle, blue	*Vinca major*	M
Petunia	*Petunia hybrida*	H
Phlox, creeping	*Phlox subulata*	M
Pink, cheddar	*Dianthus gratianopolitanus*	M
Pink, Helen allwood	*Dianthus X allwoodii*	H
Pink, rainbow	*Dianthus chinensis*	M
Poinsettia	*Euphorbia pulcherrima*	L
Poppy, California	*Eschscholizia californica*	M
Primrose, Mexican evening	*Oenthera speciosa*	M
Primrose, silver evening	*Oenothera macrocarpa*	M
Pygmy torch	*Amaranthus hypochondiracus*	H
Rock soapwort	*Saponaria ocymoides*	M
Rose, moss	*Portulaca grandiflora*	H
Safflower	*Carathamus tinctorius*	M
Sea kale	*Crambe maritima*	H
Snapdragon	*Antirrhinum majus*	H
Speedwell, woolly	*Veronica incana*	H
Splendens sea thrift	*Armeria maritima*	M
Spurge, cushion	*Euphorbia polychroma*	M
Star flower, Arabian	*Ornithogalum arabicum*	L
Starfish flower	*Stapelia gigantea*	M
Stars of Persia	*Allium christophii*	H
Statice, German	*Goniolimnon tataricum*	M
Statice, seafoam	*Limonium perezii*	L
Statice, wavyleaf	*Limonium sinuatum*	L

Table continued on next page.

Table C.1 (Continued)

Common Name	Scientific Name	Tolerance
	Forbs (continued)	
Stock, hoary	*Matthiola incana*	H
Stonecrop	*Sedum* spp.	M
Strawberry, barren	*Waldsteinia ternata*	M
Sundrops	*Oenother fruticosa*	M
Sunflower	*Helianthus annuus*	M
Sweet pea	*Lathyrus japonica*	M
Sweet William	*Dianthus barbatus*	M
Thistle, globe	*Echinops* spp.	H
Throatwort, blue	*Trachelium caeruleum*	L
Thyme	*Thymus* spp.	M
Tickseed, large-flowered	*Coreopsis grandiflora*	M
Treasure flower	*Gazania* spp.	H
Valerian, red	*Centranthus ruber*	M
Vinva	*Catharanthus roseus*	L
Virginia creeper	*Parthenocissus quinquefolia*	H
Wormwood, beach	*Artemisia stelleriana*	M
Yarrow, common	*Achillea millefolium*	M
Zinnia	*Zinnia elegans*	M
	Herbaceous Crops – Fibers, Grain, and Special Crops	
Artichoke, Jerusalem	*Helianthus tuberosus*	M
Barley	*Hordeum vulgare*	H
Canola or rapeseed	*Brassica campestris*	H
Canola or rapeseed	*Brassica napa*	M
Chickpea	*Cicer arietinum*	M
Corn	*Zea mays*	M
Cotton	*Gossypium hirsutum*	H
Crambe	*Crambe abbyssinica*	M
Flax	*Linum usitatissimum*	M
Guar	*Cyamopsis tetragonoloba*	H
Kenaf	*Hibiscus cannabinus*	H
Lesquerella	*Lesquerella fenderli*	M
Oats	*Avena sativa*	H
Peanut	*Arachis hypogaea*	M
Rice, paddy	*Oryza sativa*	L
Roselle	*Hibiscus sabdariffa*	M
Rye	*Secale cereale*	H
Safflower	*Carthamus tinctorius*	M
Sesame	*Sesamum indicum*	L
Sorghum	*Sorghum bicolor*	M
Soybean	*Glycine max*	M
Sugarbeet	*Beta vulgaris*	H
Sugarcane	*Saccharum officinarum*	M
Sunflower	*Helianthus annus*	M
Triticale	*X Tritiosecale*	H
Wheat	*Triticum aestivum*	M
Wheat, durum	*Triticum turgidum, var durum*	H
	Herbaceous Crops – Grasses and Forage Crops	
Alfalfa	*Medicago sativa*	M
Alkaligrass	*Puccinellia airoides*	H
Alkali sacaton	*Sporobolus airoides*	H
Barley (forage)	*Hordeum vulgare*	M
Bentgrass, creeping	*Argostis stolonifera*	M
Bermudagrass	*Cynodon dactylon*	H
Bluestem, Angleton	*Dichanthium aristatum*	M

Table continued on next page.

Table C.1 (Continued)

Common Name	Scientific Name	Tolerance
Herbaceous Crops – Grasses and Forage Crops (continued)		
Broadbean	*Vicia faba*	M
Brome, mountain	*Bromus marginatus*	M
Brome, smooth	*Bromus inermis*	M
Bufflegrass	*Pennisetum ciliare*	M
Burnet	*Poterium sanguisorba*	M
Canarygrass, reed	*Phalaris arundinacea*	M
Clover, alsike	*Trifolium hybridum*	M
Clover, Berseem	*Trifolium alexandrinium*	M
Clover, Hubam	*Melilotus alba*	M
Clover, ladino	*Trifolium repens*	M
Clover, Persian	*Trifolium resupinatum*	M
Clover, red	*Trifolium pratense*	M
Clover, strawberry	*Trifolium fragiferum*	M
Clover, sweet	*Melilotus* sp.	M
Clover, white Dutch	*Trifolium repens*	M
Corn (forage)	*Zea Mays*	M
Cowpea (forage)	*Vigna unguiculata*	M
Dalligrass	*Paspalum dilatatum*	M
Dhaincha	*Sesbania bispinosa*	M
Fescue, tall	*Festuca elatior*	M
Fescue, meadow	*Festuca pratensis*	M
Foxtail, meadow	*Alopecurus pratensis*	M
Glycine	*Neonotonia wightii*	M
Gram, black	*Vigna mungo*	L
Grama, blue	*Bouteloua gracilis*	M
Guinea grass	*Panicum maximum*	M
Hardinggrass	*Phalaris tuberosa*	M
Kallargrass	*Leptochloa fusca*	H
Kikuyugrass	*Pennisetum clandestinum*	H
Lablab bean	*Lablab purpureus*	M
Lovegrass	*Eragrostis* sp.	M
Milkvetch, Cicer	*Astragalus cicer*	M
Millet, foxtail	*Setaria italica*	M
Oatgrass, tall	*Arrhenatherum elatius*	M
Oats (forage)	*Avena sativa*	H
Orchardgrass	*Dactylis glomerata*	M
Panicum, blue	*Pinicum antidotale*	M
Pea, pigeon	*Cajanus cajan*	L
Rape (forage)	*Brassica napus*	M
Rescuegrass	*Chloris Gayana*	M
Rye (forage)	*Secale cereale*	H
Ryegrass, Italian	*Lolium multiflorum*	M
Ryegrass, perennial	*Lolim perenne*	M
Ryegrass, Wimmera	*Lolium, rigidum*	M
Saltgrass, desert	*Distichlis spicta*	H
Sesbania	*Sesbania exaltata*	M
Sirato	*Macroptilium atropurpureum*	M
Sphaerophysa	*Sphaerophysa salsula*	M
Sudangrass	*Sorghum sudanese*	M
Timothy	*Phleum pratense*	M
Trefoil, big	*Lotus pedunculatus*	M
Trefoli, narrowleaf	*Lotus corniculatus* var *tenufloium*	M
Trefoli, broadleaf	*Lotus corniculatus* var *arvenis*	M
Vetch, common	*Vicia angustifolia*	M

Table continued on next page.

Table C.1 (Continued)

Common Name	Scientific Name	Tolerance
Herbaceous Crops – Grasses and Forage Crops (continued)		
Wheat (forage)	*Triticum angustifolia*	M
Wheat, durum (forage)	*Triticum turgidum*, var *durum*	M
Wheatgrass, standard	*Agropyron sibiricum*	M
Wheatgrass, fairway	*Agropyron cristatum*	H
Wheatgrass, intermediate	*Agropyron intermedium*	M
Wheatgrass, slender	*Agropyrn trachycaulum*	M
Wheatgrass, tall	*Agropyron elongatum*	H
Wheatgrass, western	*Agropyron smithii*	M
Wildrye, Altai	*Elymus angustus*	H
Wildrye, beardless	*Elymus triticoides*	M
Wildrye, Canadian	*Elymus canadensis*	M
Wildrye, Russian	*Elymus junceus*	H
Herbaceous Crops – Vegetable and Fruit Crops		
Artichoke	*Cynara scolymus*	M
Asparagus	*Asparagus officinalis*	H
Bean, common	*Phaseolus vulgaris*	L
Bean, lima	*Phaseolus lunatus*	M
Bean, mung	*Vigna radiata*	L
Beet, red	*Beta vulgaris*	M
Broccoli	*Brassica oleracea*	M
Brussel sprouts	*Brassica oleracea*	M
Cabbage	*Brassica oleracea*	M
Carrot	*Daucus carota*	L
Cassava	*Manihot*	M
Cauliflower	*Brassica oleracea*	M
Celery	*Apium graveolens* var *dulce*	M
Corn, sweet	*Zea mays*	M
Cowpea	*Vigna unguiculata*	M
Cucumber	*Cucumis sativus*	M
Eggplant	*Solanum melongena* var *esculentum*	M
Fennel	*Foeniculum vulgare*	L
Garlic	*Allim sativum*	M
Gram, black	*Vigna mungo*	L
Kale	*Brassica oleracea*	M
Kohlrabi	*Brassica oleracea*	M
Lettuce	*Lactuca sativa*	M
Muskmelon	*Cucumis melo*	M
Okra	*Abelmoschus esculentus*	M
Onion, bulb	*Allium cena*	L
Onion, seed	*Allium cent*	M
Parsnip	*Pastinaca sativa*	L
Pea	*Pissum sativum*	M
Pepper	*Capsicum annuum*	M
Pigeon pea	*Cajanus cajan*	L
Potato	*Solanum tuberosum*	M
Pumpkin	*Cucurbita pepo* var *pepo*	M
Purslane	*Portulaca oleracea*	M
Radish	*Raphanus sativus*	M
Spinach	*Spinacia oleracea*	M
Squash, scallop	*Cucurbita pepo* var *melopepo*	M
Squash, zucchini	*Cucurbita pepo* var *melopepo*	M
Strawberry	*Fragaria X Ananassa*	L
Sweet potato	*Ipomoea batatas*	M
Swiss chard	*Beta vulgaris*	H

Table continued on next page.

Table C.1 (Continued)

Common Name	Scientific Name	Tolerance
	Herbaceous Crops – Vegetable and Fruit Crops (continued)	
Tepary bean	*Phaseolus acutifolius*	M
Tomato	*Lycopersicon lycopersicum*	M
Turnip	*Brassica rapa*	M
Watermelon	*Citrullus lanatus*	M
Winged bean	*Psophocarpus tetragonolobus*	M
	Woody Crops	
Almond	*Prunus duclis*	L
Apple	*Malus sylvestris*	L
Apricot	*Prunus armeniaca*	L
Avocado	*Persea americana*	L
Banana	*Musa acuminata*	L
Blackberry	*Rubus macropetalus*	L
Boysenberry	*Rubus ursinus*	L
Castorbean	*Ricinus communis*	M
Cherimova	*Annona cherimola*	L
Cherry, sweet	*Prunus avium*	L
Cherry, sand	*Prunus besseyi*	L
Coconut	*Cocos nucifera*	M
Currant	*Ribes* sp.	L
Date palm	*Phoenix dactylifera*	H
Fig	*Ficus carica*	M
Gooseberry	*Ribes* sp.	L
Grape	*Vitis vinifera*	M
Grapefruit	*Citrus X paradisi*	L
Guava	*Psidium guajava*	H
Guayle	*Parthenium argentatum*	H
Jambolan plum	*Syzygium cumini*	M
Jojoba	*Simmondsia chinensis*	H
Jujube, Indian	*Ziziphus mauritiana*	M
Lemon	*Citrus limon*	L
Lime	*Citrus aurantiifolia*	L
Loquat	*Eriobotrya japonica*	L
Macadamia	*Macadamia integrifolia*	M
Mandarin orange	*Citrus reticulata*	L
Mango	*Mangifera indica*	L
Natal plum	*Carissa grandiflora*	H
Olive	*Olea europaea*	M
Orange	*Citrus sinensis*	L
Papaya	*Carica papaya*	M
Passion fruit	*Passiflora edulis*	L
Peach	*Prunus persica*	L
Pear	*Pyrus communis*	L
Pecan	*Carya illinoinensis*	M
Persimmon	*Diospyros virginiana*	L
Pineapple	*Ananas cosmosus*	M
Pistachio	*Pistacia vera*	M
Plum	*Prunus domestica*	M
Pomegranate	*Punica granatum*	M
Popinac, white	*Leucaena leucocephala*	M
Pummelo	*Citrus maxima*	L
Raspberry	*Rubus idaeus*	L
Rose apple	*Syzygium jambos*	L
Sapote, white	*Casimiroa edulis*	L
Scarlet wisteria	*Sesbania grandiflora*	M

Table continued on next page.

Table C.1 (Continued)

Common Name	Scientific Name	Tolerance
	Woody Crops	
Tamarugo	*Prosopsis tamarugo*	H
Walnut	*Juglans* spp.	L

Note: H indicates high tolerance, M indicates moderate tolerance, L indicates low tolerance.

[a] *This species has been reclassified as* Aesculus flava.

[b] *Winter King cultivar*.

[c] *This species has been reclassified as* Acer saccharum ssp. nigurm.

[d] *This species has been reclassified as* Picea laxa.

[e] *This species has been reclassified as* Styphnolobiium japonicum.

Source: R.E. Hanes, Effects of De-Icing Salts on Water Quality and Biota, *Transportation Research Board, 1976; P.D. Kelsey and R.G. Hootman, "Deicing Salt Dispersion and Effects on Vegetation Along Highways—Case Study: Deicing Salt Deposition on the Morton Arboretum," Chapter 8 in F.M. D'Itri (editor),* Chemical Deicers and the Environment, *Lewis Publishers, 1992; J. Beckerman and B.R. Lerner*, Salt Damage in Landscape Plants, *Purdue University Extension publication ID-412-W, 2009; L.G. Jull,* Winter Salt Injury and Salt-Tolerant Landscape Plants, *University of Wisconsin-Extension Publication No. A3877, 2009; C.M. Grieve, S.R. Grattan, and E.V. Maas, "Plant Salt Tolerance," Chapter 13, pp. 405-459, in: W.W. Wallender and K.K. Tanji (editors),* Agricultural Salinity Tolerance and Management, *ASCE, 2012*