Freshwater Salinization—An Expanding Impairment of Aquatic Ecosystem Health

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Chapter E of

Knowledge Gaps and Opportunities in Water-Quality Drivers of Aquatic Ecosystem Health

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Open-File Report 2023–1085

U.S. Department of the Interior
U.S. Geological Survey

U.S. Geological Survey, Reston, Virginia: 2024

Suggested citation:
Conaway, C.H., Baker, N.T., Harvey, J.W., and Gellis, A.C., 2024, Freshwater salinization—An expanding impairment of aquatic ecosystem health, chap. E *of* Harvey, J.W., Conaway, C.H., Dornblaser, M., Gellis, A., Stewart, A.R., and Green, C.T., eds., Knowledge gaps and opportunities in water-quality drivers of aquatic ecosystem health: U.S. Geological Survey Open-File Report 2023–1085, 10 p., https://doi.org/10.3133/ofr20231085.

ISSN 2331-1258 (online)

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Supplemental Information

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations

DIC	dissolved inorganic carbon
DOC	dissolved organic carbon
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
HAB	harmful algal bloom
IWS	USGS Integrated Water Science
LOC	level of concern
NWQP	USGS National Water Quality Program
TDS	total dissolved solid
USGS	U.S. Geological Survey
WMA	USGS Water Resources Mission Area

Chemical Symbols

As	arsenic
B	boron
Ca	calcium
C	carbon
Cl	chlorine
F	fluorine
Mg	magnesium
N	nitrogen
P	phosphorus
K	potassium
Ra	radium
Se	selenium
Na	sodium

Chapter E

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Purpose and Scope

This chapter addresses knowledge gaps that, if filled, could improve predictions of aquatic ecosystem health as affected by freshwater salinization. The gaps identified in this chapter are not intended to be comprehensive but are instead focused on key opportunities for the U.S. Geological Survey (USGS) Water Resources Mission Area (WMA, https://www.usgs.gov/mission-areas/water-resources). Salinity effects on beneficial uses of water are not addressed in this chapter but are covered in Chapter B of Tesoriero and others (2024), “Addressing Salinity Challenges to the Beneficial Uses of Water,” the companion Open-File Report to this publication.

Statement of the Problem

Freshwater salinization is a primary concern for human health and aquatic life. The increasing salinity of freshwater resources in the United States poses a direct threat to ecological health and beneficial uses of that water on a national scale (Stets and others, 2020). Salinity is the sum of dissolved salts in water. However, unlike seawater, which has high concentrations of sodium (Na) and chloride (Cl) ions, freshwater tends to have several ions in various concentrations—for example, calcium (Ca), Cl, magnesium (Mg), potassium (K), and sulfate. In areas with hard or more alkaline water, Na and Cl may be in lower concentrations than Ca, Mg, bicarbonate, and sulfate. In contrast, pore water or groundwater in sedimentary basins, including many areas where energy development is presently concentrated, may have salinity that is similar to or greater than seawater, with major chemical composition varying based on terrestrial processes such as evaporation, water-rock interactions, and mixing of different water types, including mixing with groundwaters that contain relict seawater (Kharaka and Hanor, 2014). These disparate sources of ions contribute to the total salinity of water which can be inferred or measured in water by determining individual ion concentrations, specific conductance, or total dissolved solids (TDS)—which includes dissolved organic components.

Salinity and salinization of freshwater have long been leading water quality issues nationally and globally. The primary effects related to ecological health are related to lethal and sublethal effects on aquatic communities, loss of biodiversity, mobilization of contaminants, and effects on the riverine carbon cycle (Kaushal and others, 2021; Stets and others, 2020). In a U.S. Geological Survey (USGS) study of water-quality trends in United States rivers, Shoda and others (2019) determined that 26 percent of sites exceeded the U.S. Environmental Protection Agency’s (EPA’s) National Recommended Water-Quality Criteria stream aquatic life level of concern (LOC) for TDS. In a similar vein, in a study of Cl trends in northern United States urban streams (Corsi and others, 2015), 29 percent of sites studied exceeded the concentration for the EPA chronic water quality criteria of 230 milligrams per liter (mg/L) by an average of more than 100 individual days per year during 2006–2011. Moreover, recent analyses of USGS water quality data across the United States have identified a multi-decadal trend of increasing salinity in rivers and streams on a continental scale (Kaushal and others, 2018; Stets and others, 2020), focused particularly in urban-influenced watersheds.

Increases in alkalinity are also associated with salt pollution, although the environmental effects of alkalinization have received comparatively less attention and are perhaps less well understood than those of salinity (Kaushal and others, 2018). Many sources release alkaline salts like bicarbonate into the environment, including weathering of impervious surfaces, fertilizer and lime use in agriculture, mine drainage, irrigation runoff, and winter use of road salt. For example, Na in road salt can act to release the alkaline salts which then wash into freshwater ecosystems. Bicarbonate, the predominant form of dissolved inorganic carbon (DIC) in natural waters, originates primarily from watershed mineral weathering; however, human activities affect riverine bicarbonate fluxes, and we still cannot estimate the net effect on the global scale (Hamilton and Raymond, 2018).

The effects of freshwater salinization are a pervasive environmental issue and further study is needed for aggressive management strategies (Kaushal and others, 2018). Research is also needed to understand how changes in salinity, and in specific major ion concentrations, are related to specific water quality drivers and how those changes might be affecting aquatic ecology and ecosystem services (Stets and others, 2020) through toxicity or contaminant mobilization. More research is also crucial to adequately understand the effects of salinization on riverine carbon cycles (Kaushal and others, 2018).

Status of Knowledge and Key Limitations

The interrelated issues of salt ions and chemical, biological, and geologic parameters and consequences on the environment is called Freshwater Salinization Syndrome (Kaushal and others, 2021), and the key conceptual elements related to aquatic ecosystems are summarized in figure E1 and table E1. The general status of knowledge and information about salinity and related water-quality drivers is summarized in table E2. Many human activities contribute to increased salinity through a variety of processes, which complicates identification of the drivers of salinity increases or generalizes their effects on aquatic ecosystems. The predominant sources of salinity are well-known, and the sources driving observed changes include anthropogenic inputs of salt such as road salt, wastewater, water treatment, brine disposal, agricultural runoff; acceleration of natural weathering or water-rock interaction via acid rain, fertilizers, acid-mine drainage; and weathering of construction and manufacturing materials such as cement, lime, and concrete (Kaushal and others, 2018). Some of the environmental factors driving changes in salinity include climate change (for example, timing and amount of precipitation related to various kinds of runoff or chemical weathering), changes in water use (for example, surface water diversion, groundwater withdrawal, irrigation), changes in land-use and land cover, and sea level rise.

Many environmental ramifications of freshwater salinization are listed by Kaushal and others (2018), and include influencing the rates of coastal ocean acidification, the effects of toxicants, the water-sediment partitioning of toxic elements, decreasing soil stability and fertility, leaching and mobilization of nutrients, controlling the quality and release of organic matter from soils to streams, and altering aquatic ecosystem community structure. Some listed effects of alkalinization include changes in dissolved organic carbon (DOC) transported by rivers, changes in dissolved carbon dioxide, and influencing the distribution of invasive mussels. A recent analysis by Stets and others (2020) highlights the loss of stream biodiversity as one reason salinization is gaining attention as a worldwide problem; also because salinization can cause metals to desorb from streambed sediment. Other factors to consider related to salinity are ecosystem-related effects (for example, on mangrove wetlands, river delta communities, invasive species distribution, cyanobacteria community composition).

The ecosystem health gap analysis team for the WMA Water Quality Program identified five freshwater salinization ecological health impairments:

15. Community structure shifts related to toxicity or sensitivity to salinity,
16. Salt-tolerant invasive species,
17. Alteration of nutrient and organic matter cycling,
18. Mobilization of contaminants and bioactive elements, and
19. Alteration of soil properties and loss of structure.

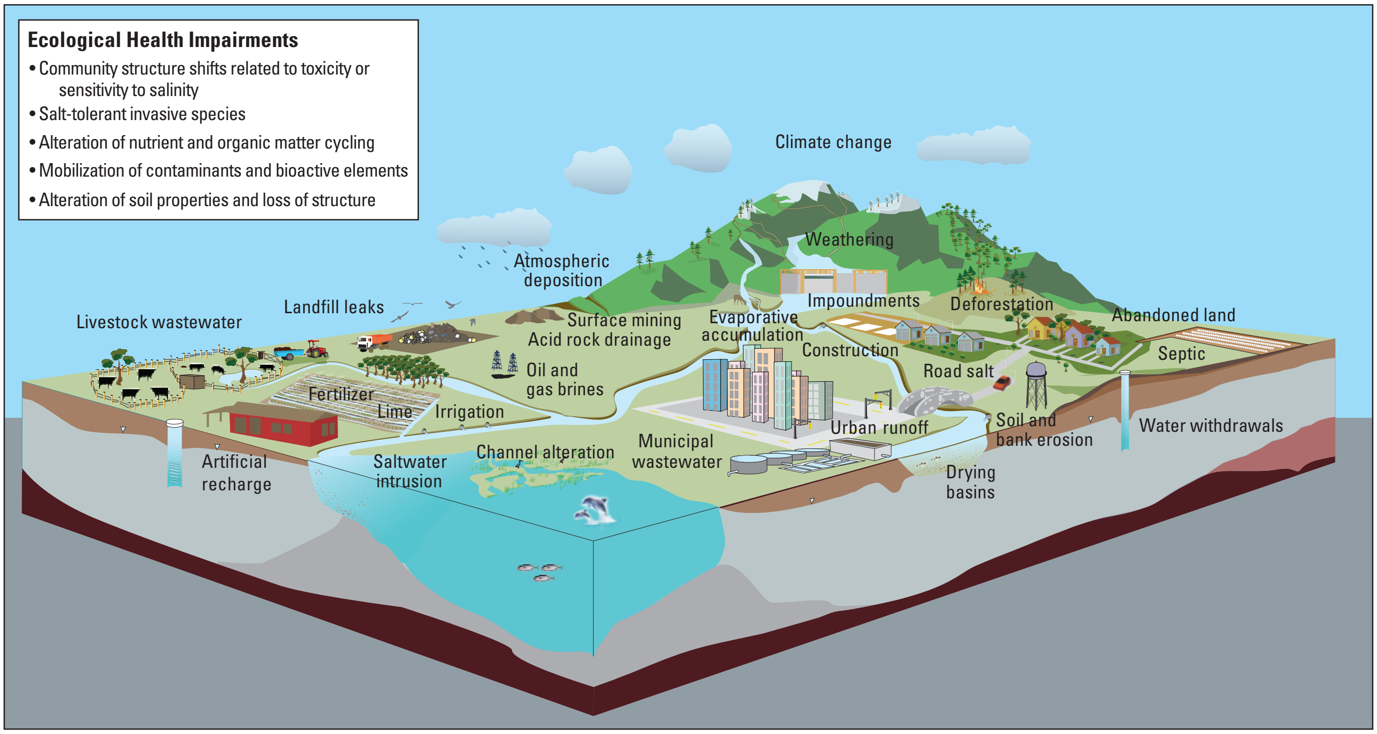

Figure E1. Diagram of sources and drivers of freshwater salinization with potential ecological health impairments.

Table E1. Summary table for freshwater salinity gap analysis for aquatic ecosystem health identified by the U.S. Geological Survey (USGS) and grouped by chemical salinization and ecosystem risks from salinization.

[CH_4, methane; H_2S, hydrogen sulfide]

What	Gap	Why	How
Chemical landscape of salinization			
Gap 1a Predicting and understanding changes	An understanding of event-based, seasonal, and long-term changes in salinity	Need to extrapolate measurements and model results over a wide range of hydrologic and climate variables	Monitor salinity with high frequency sensors. Develop long-term continuous data.
Gap 1b Loadings and pathways	Understanding of transport, storage, and elucidation of sources	Crucial for management, model prediction, and remediation	Watershed-ecosystem mass balance approach. Development and assessment of geochemical and isotopic tools for identifying sources.
Ecosystem risks from salinization			
Gap 2a Mobilization of chemical cocktails	Uncertainty regarding how different salt ions and mixtures across range of salinity affect biota, ecological communities, and ecosystem functions and services	Salinity causes mobilization of toxic chemicals and nutrients that affect biodiversity and ecosystem processes.	Survey of data on major ion ratios related to salinity in freshwater systems. Develop predictive models for geochemical water type in groundwater based on local geologic, hydrologic, and climatic conditions.
Gap 2b Effects of sea level rise	Complex geochemical modification of groundwater by seawater intrusion affecting community structure from microbes to forests	Ecosystem effects include microbial production and release of CH_4 or toxic H_2S, and salinity alteration of plant communities, carbon sequestration, and soil elevation change in coastal wetlands.	High-frequency continuous sensor output data investigation of salinity controls on dissolved organic matter processing, microbial products such as CH_4 and H_2S, resulting carbon burial and soil elevation change, including research on how saltwater intrusion affects soils (formation of plugs, dispersion of aggregates).
Gap 2c Changing community structure	Understanding of effects of salinization (for example, sea level rise and saltwater intrusion) on ecosystem health and community structure.	Changes affect coastal carbon sequestration, invasive species, and loss of plant communities anchoring coastal wetlands that transform nutrients and stabilize coastline.	Detailed (high frequency sensor) investigation of salinity controls on dissolved organic matter quantity and composition in coastal water, and on microbial products.

Because of the increasing concern regarding salinity related to increasing prevalence, ecological toxicity, and corrosion issues, there are major research and significant papers that continue to be published. Recent work on freshwater salinization by road salts and urbanization has been published by Moore and others (2020) on deicing; Kaushal and others (2018) on continental scale; Stets and others (2020) on landscape drivers in United States rivers; and Dugan and others (2017, 2020) on freshwater lakes. Recent work highlighting ecological effects includes Moore and others (2020) on conductivity and chloride exceedances of EPA aquatic life criteria in streams; and Hintz and Relyea (2017) work on responses of fish and zooplankton, and McCormick and others (2011) on responses of periphyton communities to freshwater salinization. Related to groundwater-surface water interaction, brackish groundwater assessments and information are presented by McMahon and others (2016) and in a USGS Professional Paper by Stanton and others (2017). Sprague and others (2019) presented recent work on changing salinity at multiple geographic scales using streamflow data and results from probabilistic and targeted monitoring, and Murphy and Sprague (2019) on the effects from streamflow trends and changes in watershed management. Work focusing on USGS Integrated Water Science (IWS) basins is presented by Rumsey and others (2017) on dissolved solids delivery to streams in the Upper Colorado River Basin.

Radionuclides

Saline water, either from road salts or from oil and gas development and production activities, has the potential to mobilize natural and contaminant radionuclides, such as radium-226 (^{226}Ra) and radium-228 (^{228}Ra) (Cozzarelli and

Table E2. Single-factor constituents of concern, drivers, and indicators of aquatic ecosystem health identified by the U.S. Geological Survey (USGS).

[Included are notations on sources and controlling factors, regions of concern, benchmarks for aquatic life and prevalence of exceedances, data availability, and references. CMC, criterion maximum concentration; CCC, criterion continuous concentration. IWS, Integrated Water Science; NAWQA, National Water Quality Assessment Project; EPA, U.S. Environmental Protection Agency; 303(d), Clean Water Act Section 303(d); TDS, total dissolved solids; LOC, level of concern; mg/L, milligrams per liter; %, percent; NORM, naturally occurring radioactive materials; TENORM, technologically enhanced naturally occurring radioactive materials; U-Th, uranium-thorium.]

Category, constituent, or driver	Source areas, controlling factors, and (or) value as an indicator	Areas or regions of concern	Benchmarks for aquatic life and information about exceedances	Data availability for analysis
Salinity[1]	Road salt, groundwater extraction, mining, oil and gas produced water, agricultural return flows, sea level rise, surface water diversion, stormwater, urban runoff and wastewater discharge, landscape disturbance, drinking water chlorination (Anning and Flynn 2014)	National, global, and includes USGS IWS basins.	See TDS, chloride, and conductivity below.	See TDS, chloride, and conductivity below.
TDS[2]	Road salt, groundwater extraction, mining, oil and gas produced water, agricultural return flows, sea level rise, surface water diversion, stormwater, urban runoff and wastewater discharge, landscape disturbance, drinking water chlorination (Anning and Flynn 2014).	National, global, and includes USGS IWS basins.	EPA National recommended water criteria stream aquatic life: LOC 500 mg/L; 26% of 208 continental United States stream sites exceeded LOC (Shoda and others, 2019).	Anning and Flynn 2014; Stanton and others, 2017. USGS discrete data (USGS, 2022).
Chloride	Municipal and industrial discharges, septic systems, and road-salt runoff.	National, global, and includes USGS IWS basins, especially areas with increasing urban land use.	Federal EPA CMC is 860 mg/L; CCC is 230 mg/L. Corsi and others (2015) found the CCC exceeded in 29% of major cities investigated	USGS discrete data (USGS, 2022)
Conductivity[3]	Used to estimate salinity/TDS.	Increasing in all human-dominated landscapes, that is, in streams in urban and agricultural areas, and areas with a mix of the two (Stets and others, 2020)		Fanelli and others, 2019. USGS discrete data (USGS, 2022). USGS real-time data (https://waterwatch.usgs.gov/wqwatch/?pcode=00095). USGS National Water Quality Watch (https://waterdata.usgs.gov/nwis/current/?type=quality&group_key=NONE).
Radionuclides[4]	Radionuclides may be important in certain environments/regions (Szabo and others, 2020). NORM and TENORM an issue in oil fields and related waste disposal (Cozzarelli and others, 2017; McDevitt and others, 2019).	Groundwater from naturally U-Th rich rock, contamination from oil and gas exploration and extraction and waste disposal.	Not captured in EPA's recommended aquatic life criteria.	USGS produced water database (https://eerscmap.usgs.gov/pwapp/) USGS NAWQA (https://www.usgs.gov/programs/national-water-quality-program/national-water-quality-assessment-project-nawqa) (Szabo and others, 2020).

[1] Strictly speaking is only dissolved salts, but often used interchangeably with TDS—see entry below.

[2] All dissolved material, can include organic solutes.

[3] Specific conductance.

[4] Radium-228, Radium-226.

others, 2017; McDevitt and others, 2019). The geochemical mobility of Ra is often controlled by either sorption or co-precipitation with sulfate or carbonate minerals. For example, elevated sediment radium from co-precipitation with carbonate was observed downstream of produced water discharge in Wyoming streams (McDevitt and others, 2019). Alternatively, mobilization due to desorption is shown in a study on the mobilization of radium and radon by deicing salt contamination of groundwater under a parking lot in Connecticut that concluded that salt contamination of groundwater could increase the potential for human exposure to these radioactive and carcinogenic elements (McNaboe and others, 2017). High concentrations of naturally occurring Ra are known to cause human health effects (EPA, 2000). However, there is a knowledge gap on the effects of water quality shifts (dilution or acidification) on Ra distribution downstream of contaminated sites (Cozzarelli and others, 2017; McDevitt and others, 2019), and the health effects of Ra on wildlife are not well known (McDevitt and others, 2019). Thus, to understand the potential for long-term downstream contamination from mobilized radionuclides, there is the need to study the environmental behavior of these chemicals along complex hydrologic flowpaths (Kaushal and others, 2021). Further discussion of the significance of environmental radionuclides can be found in the companion report, chapter C "Geogenic Water-Quality Effects on Beneficial Uses of Water" (Tesoriero and others, 2024).

Knowledge Gaps in Salinity Drivers of Ecosystem Health

Salinization is increasing in many parts of the United States and globally and is a complicated emerging problem for ecosystem health (Kaushal and others, 2021). Although salinity is decreasing in some areas, which may reflect successful mitigation strategies (Rumsey and others, 2017) or salinity cycles related to changes in precipitation (Tillman and others, 2019), increases are evident especially in urban areas and dryland environments (Stets and others, 2020). For USGS Water Mission Resources Area (WMA) research, we divide knowledge gaps into needs for increased understanding into two broad classes of gaps:

1. Defining the chemical landscape of salinization, which includes:
    a. predicting and understanding changes in salinity, and
    b. salinity loadings and pathways.
2. Evaluating ecosystem risks from salinization, which include:
    a. risks related to salinity mobilization of "chemical cocktails,"
    b. effects of sea level rise on coastal ecosystems, and
    c. the effects of salinization on changing community structure (from microbes to HABs to invasive species).

We present these gaps in detail below and provide a summary in table E1.

Gap 1. Defining the Chemical Landscape of Salinization

The first class of gaps in defining the chemical landscapes of salinization include:

Gap 1a. Predicting and Understanding Changes in Salinity

Decadal-scale salinization has been well-documented in arid, semi-arid, humid, and urban regions across the United States and globally (Kaushal and others, 2021; Stets and others, 2020). Some of the major gaps in understanding the drivers of salinity changes include the role of seasonal trends and an understanding of the landscape processes and broad regional changes that affect water quality. These changes can be important, such as in the case of increased salinity during low-flow conditions when biotas are most sensitive to changes in water quality (Stets and others, 2020). Climate driven changes include reduction in precipitation, increases in aridity, and other long-term changes contributing to salinization include increasing urbanization and water use (Vengosh, 2014). In addition, more information is needed on how storm and snow events influence salinity and related contaminant load across a variety of landscapes (Corsi and others, 2015; Kaushal and others, 2021). Better understanding of these short-term and long-term drivers should allow us to better predict and manage salinity in the future. Consequently, we propose that research should be carried out by focusing on target basins to address these questions:

- How might the rates of supply from salinity sources change due to climate change?
- What event, seasonal or interannual trends of salinity, exist in river and lake environments (including storm events, droughts, snow events, wind-blown dust from exposed shorelines)?
- How might the rates of supply from salinity sources change due to land use change including changes in groundwater pumping, irrigation, and energy development?
- How might the rates and supply from salinity sources change due to infrastructure change (flow management, water diversions, interbasin transfers)?
- Where and at what rate are anthropogenic sources—such as road salt, liming and fertilizer, and septic systems—increasing salinity in the unsaturated zone and shallow groundwater causing mobilization of chemicals in the soil

profile that may ultimately be carried to surface-water aquatic ecosystems?

- How is salinization of rivers and lakes related to variable inputs from runoff and groundwater across seasonal to decadal time scales?

For these events, seasonal, interannual and long-term trends, work is required using high-frequency continuous sensor output data for salinity, preferably across a range of land use types and precipitation patterns (rain, snow, snow melt, arid, humid, urban, agriculture) combined with traditional streamflow monitoring and new approaches to modeling and links to other geochemical data (Kaushal and others, 2021). Long-term high frequency data would allow for the determination of peaks, response time, and hysteresis in salinity versus flow across different time scales from storm events to interannual trends. These data could also be useful to determine the time scale of exceedances of water quality criteria, and longer records of these data could be used to determine whether there has been an increase or decrease in the number of days exceeding those criteria. Deliverables for this work should be high-frequency continuous sensor data for target basins that can be used to better understand and predict natural and human-accelerated salinization on short-term to decadal scales, and an interpretation of the processes driving these changes. Beyond adopting high-frequency continuous sensor data approaches, some basic questions of seasonality and the relationship to streamflow could be explored in many places with existing and extensive discrete data when combined with modeling efforts such as weighted regressions on time, streamflow, and season (Oelsner and others, 2017).

Gap 1b. Salinity Loadings and Pathways

Qualitative knowledge of loading, response time, and hydrologic flowpaths of salinity from existing sources is crucial to understanding and managing salinization of aquatic ecosystems. Establishing loadings and pathways is essential for determining the legacy response time of current salinity loads, as well as predicting the results of increasing loads. Salt from atmospheric deposition, evaporation of surface water, or anthropogenic salinity sources can accumulate in water and soils in the saturated or unsaturated zone and later can be flushed downward or laterally. The flushing can be caused by changes in land use such as removing vegetation or changing vegetation type (for example, natural to cropland), or changes in hydrologic budget through increased rainfall, irrigation, or even sea level rise. Storage and flushing of salinity are well-documented in dryland environments (Vengosh, 2014), but less so in urban areas or basins with anthropogenic salinization (Lax and Peterson, 2008; Ledford and others, 2016).

To address this gap, we support following the recommendation of Kaushal and others (2021) to develop a watershed-ecosystem approach. The initial screening is a mass balance of TDS at the regional to national scale to better understand how different hydrogeologic settings and land uses affect river loads. Next is a partitioning of individual major components (for example, Na, Cl, sulfate, bicarbonate) for target watersheds such as the USGS IWS basins; including an evaluation of "hot spots," such as near roadways, wildfire burn areas, wastewater discharge, urban areas, resource development and extraction, and groundwater. We note that refining the mass balance of TDS to the level of major components may be limited by available data and requires new data collection.

To complement this approach, forensic work on determining the relative contributions of salinity sources could be carried out. Where there are multiple sources of salinity to a system, the integration of multiple chemical and isotopic tracers is required to distinguish between these sources (Vengosh, 2014). Common tracers for salinity sources include chemical ratios (for example, Na/Cl, Br/Cl, B/Cl, Ca/Cl, SO_4/Cl) and isotopic ratios (for example, $\delta^{18}O$ and $\delta^{2}H$ in H_2O, $\delta^{11}B$, $\delta^{34}S$, $\delta^{34}S$ and $\delta^{18}O$ in SO_4, $^{36}Cl/Cl$, $^{129}I/^{127}I$, $^{87}Sr/^{86}Sr$). To quantitatively relate sources of salinity to water quality observations and predictions in target basins, projects could be pursued to evaluate data availability and application of these geochemical tools. Deliverables for projects could include identification of the best combination or integration of tracers in these systems, a compilation of available data, and potential tracers for reuse water. Other potential work identified by USGS to provide better quantification of the sources and causal factors includes:

- Examination or acquisition of road-salt use data to attribute cause and determine if "legacy" road salt is a concern,
- Determining atmospheric dry (aerosol or aeolian dust) deposition rates of salt to determine the relative importance to wet deposition rates, and
- Compiling TDS estimates from wastewater to better understand its role in salinization.

Gap 2. Evaluating Ecosystem Risks from Salinization

The second class of gaps in evaluating ecosystem risks from salinization include:

Gap 2a. Salinity Mobilization of Chemical Cocktails (Mixtures)

There is much uncertainty regarding how different salt ions and mixtures across a range of salinity affect biota, ecological communities, and ecosystem functions and services (Kaushal and others, 2021). Research is needed to understand how increases in salinity, and in specific major ion concentrations, might be affecting aquatic ecology and ecosystem services (Stets and others, 2020) through toxicity or contaminant mobilization. Much of the work on the environmental effects of salinization has focused on Cl; but different components of salinity—Na, Mg, Ba, bicarbonate, sulfate, silica—are recognized to have different effects on the health of aquatic systems. Examples include (1) different salts influence toxicity to aquatic organisms (Kaushal and others, 2018); (2) mobilization of geogenic contaminants such as fluoride (F), arsenic (As), B, and Ra by salinization (Vengosh, 2014); and (3) salinization can cause leaching and mobilization of bioreactive elements (carbon [C], nitrogen [N], phosphorus [P]) from soil to water in streams (Kaushal and others, 2018). A survey of the importance and availability of data on major ion ratios related to salinity in freshwater systems would be beneficial to understanding the effects of salinization. In addition, predictive models for geochemical water types in groundwater that are based on local geologic, hydrologic, and climatic conditions could be developed. There is crossover in examining major ion chemistry controlling speciation with the presentation in chapter C "Geogenic Water-Quality Effects on Beneficial Uses of Water" in the companion report (Tesoriero and others, 2024). Consequently, we propose:

- Developing prediction capability to determine major ion ratios and effects on beneficial uses via corrosion, mobilization of contaminants, and suitability for use;
- Examination of the role of salinity in the prediction of health-related geogenics (for example, F, As, Se, B, Ra); and
- Inclusion in models for the prediction of water types based on geochemical processes (for example, base cation exchange, freshening, generation of dissolved inorganic carbon [DIC] by oxidation of organic matter).

Gap 2b. Effects of Sea Level Rise on Coastal Ecosystems

The effects of sea level rise and saltwater intrusion on ecosystem health and community structure represents another important research area (Vengosh, 2014; Kaushal and others, 2021). The complex geochemical modification of groundwater by seawater intrusion and displacement is considered above under sections Gap 1b "Salinity Loadings and Pathways" and Gap 2a "Salinity Mobilization of Chemical Cocktails (Mixtures)." Research is also crucial for determining how saltwater intrusion affects soils (formation of plugs, dispersion of aggregates). Ecosystem effects include modification of microbial community structure resulting in changes in production and release of CH_4 or toxic H_2S. Salinity alteration of DOC export, plant community structure, and coastal wetland carbon sequestration represents another important research area (Kaushal and others, 2021). Research specific to USGS WMA National Water Quality Program (NWQP) could include detailed (high-frequency continuous sensor output data) investigation of salinity controls on dissolved organic matter quantity and composition in coastal water, and on microbial products such as CH_4 and H_2S, which can also be determined with continuous sensors.

Gap 2c. The Effects of Salinization on Changing Community Structure (From Microbes to Harmful Algal Blooms to Invasive Species)

There are major research gaps and management questions on the topic of salinization and ecosystem effects (Vengosh, 2014; Kaushal and others, 2021). These gaps include both knowledge of direct effects on organisms and biodiversity through toxicity related to chloride, as well as indirect effects such as the alteration of microbial community structure through mobilization of nutrients and contaminants related to salinization (Kaushal and others, 2021). Salinization of surface water can trigger harmful algal blooms (HABs) with profound effects on fish, salamanders, and mussels (Vengosh, 2014). Salinization also has effects on the distribution and success of salt-tolerant invasive species (Kaushal and others, 2021). Research gaps on HABs and invasive species are covered in other programs within USGS and WMA; however, as described above under Gap 1a "Predicting and Understanding Changes in Salinity," high-frequency continuous sensor output data for salinity, preferably across a range of land use types and precipitation patterns (rain, snow, snow melt, arid, humid, urban, agriculture) combined with new approaches to modeling and links to other geochemical data could greatly contribute to research on these topics.

Priorities and Timelines for Addressing Gaps

Priorities

Gap 1a. Predicting and Understanding Changes in Salinity

This gap has high value scientifically both regionally and nationally, but is given number 2 rank in priority because this is a "long term" problem compared to the more immediate needs addressed in Gap 1b.

Gap 1b. Salinity Loadings and Pathways

This work provides information for management in the "now", and there is high value in water-stressed areas and at-risk areas.

Gap 2a. Salinity Mobilization of Chemical Cocktails (Mixtures)

There is good potential for process understanding inclusion into models, but effort may require substantial geochemical expertise. The chemistry and concepts are complex, and the value of data may be specific to USGS Integrated Water Science (IWS) basins but the knowledge gained is applicable across many aquatic systems.

Gaps 2b and 2c. Sea Level Rise, Salinization, and Changing Community Structure

The work is high value within areas, but knowledge transfer to other IWSs may be low because ecosystem communities are somewhat unique and therefore the knowledge gained is not widely applicable. In addition, the factors and drivers extend beyond salinity.

Timelines

Near-Term (2–5 Years)

Approaches to fill knowledge gaps that fall into a near-term (2-year) level of implementation consist of plans for the development and identification or deployment of high-frequency continuous sensor output data for (1) salinity in existing IWSs, (2) the development of lists and methods for forensic tools for salinity sources in existing IWSs, and (3) the development of data collection and management plans. Other approaches in the near-term are related to a watershed-ecosystem type approach in IWSs and include developing mass balance of TDS in IWSs and identification and evaluation of salinity “hot spots” in those IWSs, such as near roadways, wildfire burn areas, wastewater discharge, urban areas, resource development and extraction, and groundwater.

Mid- to Long-Term (5–10 Years)

Approaches to fill knowledge gaps that fall into mid- (5-year) to long-term (10-year) implementation timeframes are (1) the development of long-term ecological data sets, (2) refining the focus in watershed-ecosystem mass balance approaches to individual major components of salinity, (3) developing and assessing results of management actions, and (4) refining model predictions with long-term, high-frequency sensor data.

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Moffett Field Publishing Service Center
Manuscript approved October 12, 2023
Edited by Kathryn Pauls
Illustration support by Kimber Petersen
Layout by Cory Hurd