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Reversing Freshwater Salinization: A Holistic Approach

Inland freshwater salinity is rising globally, a trend that threatens water and food supplies, civil infrastructure, and freshwater ecosystems.

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Receiving Waters Source Water Protection Stormwater

There is an urgent need to reverse freshwater salinization by engaging practitioners, scientists, policy makers, entrepreneurs, and the public.

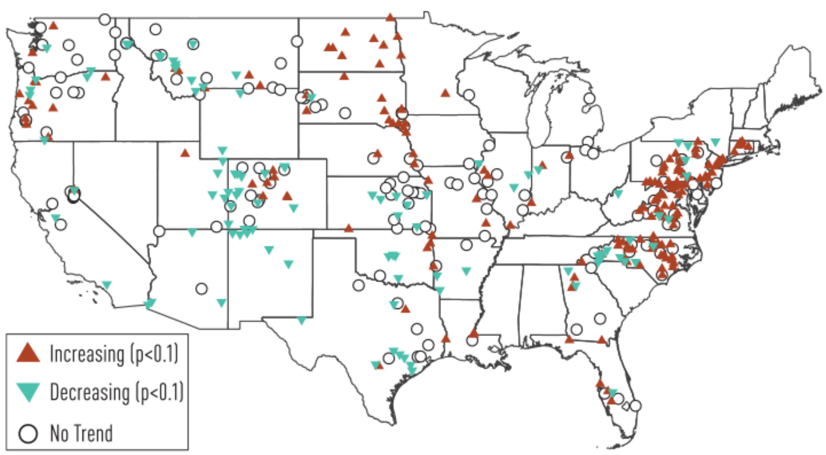
What Is Freshwater Salinization?

FRESHWATER SALINIZATION refers to an increase in the total dissolved solids concentration of freshwater resources (groundwaters, streams, reservoirs, etc.) relative to historic background levels. In the past, freshwater practices and policies, are driving freshwater salinization throughout the United States (Kaushal et al. 2005). Major contributors include road salting in the densely populated Northeast and Mid-Atlantic, agriculture in the Midwest and South, irrigation practices in the arid West, and seawater intrusion in coastal regions (Figure 1). A recent U.S. Geological Survey (USGS) assessment of 422 streams across the nation concluded that "freshwaters are being salinized rapidly in all human-dominated land use types" (Stets et al. 2020). At continental scales, inland freshwater salinization manifests as increases in (1) ionic strength; (2) base cations; and (3) alkalinity, and consequently pH. This widespread pattern has been termed the "freshwater salinization syndrome" (Kaushal et al. 2018).

What Are the Impacts?

Water Supply

FRESHWATER SALINIZATION could be among the most expensive water supply challenges our nation has ever faced. For example, rising sodium concentrations in one of two drinking water sources for 2 million people in northern Virginia prompted the local water purveyor, Fairfax Water, to initiate planning-level discussions for a possible reverse osmosis (RO) treatment upgrade. The estimated cost is $1 billion to treat 125 million gallons per day (MGD), not accounting for operation and maintenance costs, a higher carbon footprint, reduction in water production capacity (e.g., from 125 MGD presently to approximately 100 MGD after the RO upgrade, with the difference going to "reject" water or brine concentrate), and the environmental challenges associated with inland brine disposal (Tong and Elimelech 2016). Scaled up to the >50 million people living in the Mid-Atlantic (where salinity is rising quickly; see Figure 1), the capital costs of "desalinating freshwater" in the region could exceed $50 billion.



Source: Data from Stets et al. 2020

Figure 1. A USGS assessment of trends (from 1992 to 2012) in flow-weighted electrical conductance, a measure of salinity, in 422 U.S. streams

Water Quality and Ecosystem Health

FRESHWATER SALINIZATION CAN alter evapotranspiration rates and threaten freshwater fisheries and the ecological health of inland waters (Perri et al. 2020, Kaushal et al. 2021). Freshwater salinization can also displace and mobilize "chemical cocktails" of nutrients and heavy metals previously sequestered in soils and aquatic sediments (Kaushal et al. 2019).

FOR COMMUNITIES THAT CANNOT afford RO upgrades, salinization of water supplies can accelerate corrosion of water supply and distribution systems, and threaten human health by mobilizing lead, copper, and other heavy metals (Pieper et al. 2018, Nguyen et al. 2011, Hong and MacAuley 1998). Salinization can also alter the perception of potability; at high enough concentrations, sodium and other salts degrade the taste of drinking water (Dietrich and Burlingame 2015, WHO 1996). Sodium concentrations above 20 mg/L in drinking water endanger the health of individuals on sodium restricted diets, a problem exacerbated by an aging U.S. population (EPA 2003).

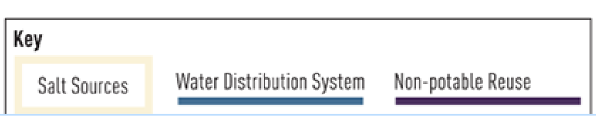
Food Supply

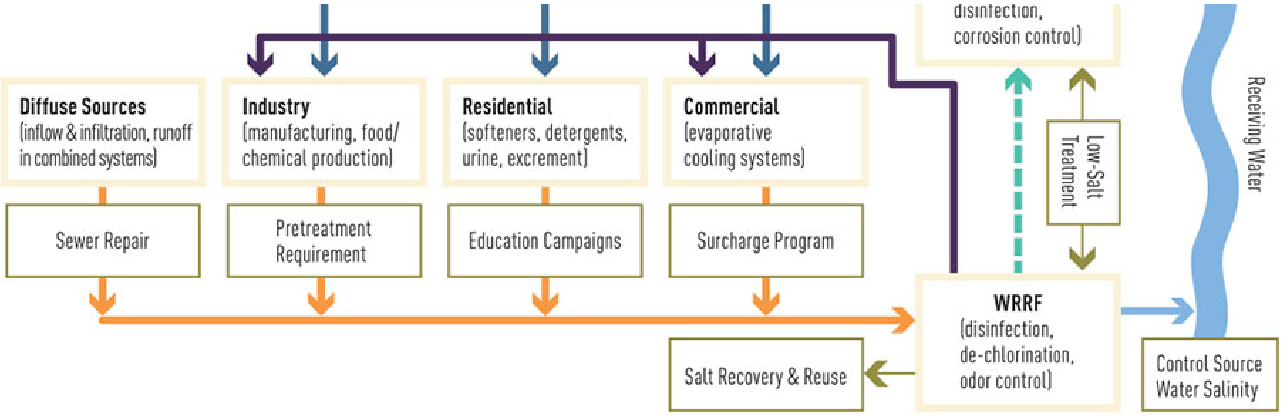
FRESHWATER SALINIZATION reduces agricultural productivity in areas reliant on irrigation. California's agricultural output (equal to 12% of the U.S. total) was reduced by 7.9% (or $3.7B) in 2014 due to salinization (Welle and Mauter 2017). Globally, >40% of the world's food production is impacted by salinization (Schwabe et al. 2006).

Opportunities for Reversing Freshwater Salinization

FRESHWATER SALINIZATION CAN be halted, or even reversed, by "rewriting the book" on the design and operation of engineered systems (see Figure 2). Engineering infrastructure contributes to freshwater salinization through:

- Discharge of salt to surface waters and ground-waters from transportation systems (e.g., wash-off of deicers applied to roads and freeways during snow melt and storm events), wastewater and industrial discharges, municipal stormwater drainage systems, tile drains in agricultural settings, energy and resource extraction activities, and the weathering of urban infrastructure (Snodgrass et al. 2017, Bhide et al. 2021, Taguchi et al. 2020, Schwabe et al. 2006, Timpano et al. 2015, Entrekin et al. 2011, Tippler et al. 2014).
- Mobilization of geogenic sources of salt by physical erosion of salt-bearing sediments following the construction of municipal stormwater drainage networks, by exchange and displacement of cations and metals from soil during road deicing, by mixing water from deep (briny) aquifers into fresh shallow aquifers following the installation of multiple-aquifer well systems, and by mobilizing brine from deep aquifers during hydraulic fracturing operations (Walsh et al. 2005, Rossi et al. 2017, Mannix et al. 2019, Khan et al. 2021).
- Evaporative concentration of salts already in freshwaters by evapotranspiration in the case of food and biofuel production (which will worsen with climate change) and evaporative cooling in the case of wet-cycle thermoelectric power plants (Le et al. 2011, Fleischli and Hayat 2014). Ironically, water conservation can increase wastewater salinity, with implications for wastewater reuse and the ecosystem health of the over 900 effluent-dominated streams in the U.S. (Schwabe et al. 2020, Rice and Wester-hoff 2017).





Source: Courtesy of Stanley Grant and Ayella Maile-Moskowitz

Figure 2. Schematic diagram illustrating salt sources and intervention opportunities in drinking water plants (DWPs), potable and non-potable water distribution systems, sewage collection systems, water resource recovery facilities (WRRFs), and inland freshwaters. Importantly, salts are not removed by conventional water or wastewater treatment and therefore pass directly through the DWP and WRRF

Regional Challenges

SNAPSHOTS OF THE salinization challenges confronting various regions of the U.S. include:

Northeast and Mid-Atlantic States

RAPID SALINIZATION OF INLAND surface waters threatens the long-term viability of local drinking water supplies, as well as stream and riparian ecosystems. Likely salt sources include: (1) deicer wash-off from transportation infrastructure; (2) inland discharge of reclaimed water; (3) untreated sewage from leaking sewage collection systems, combined sewer overflows, and failing septic systems; (4) mineral resource extraction; and (5) the dissolution of aging concrete infrastructure.

Midwest States

IN ILLINOIS, WISCONSIN, IOWA, and Minnesota, multiple cycles of glaciation created stratified aquifer sequences grading from shallow freshwater to deep brines. The combination of shallow fresh groundwater, naturally fertile soils, and large-scale irrigation drainage infrastructure supports one of the most productive agricultural regions in the world. Freshwater salinization in the region arises from: (1) deicer wash-off from transportation infrastructure; (2) multiple aquifer well systems that create open conduits for deep brines to mix with fresh shallow aquifers; and (3) widespread agricultural amendments, irrigation, tile drainage, and intensified evapotranspiration.

Texas

ACCORDING TO THE TEXAS Desalination Association, the state's 100 desalination facilities currently produce 138 MGD of fresh water from brackish groundwater, but more inland desalination capacity will be required to meet growing demand for fresh water (TDA, n.d.). Disposal of brine from these facilities adds salt to freshwater resources that are already under significant salinity stress (e.g., the Rio Grande is designated as one of North America's most imperiled rivers, in part due to high salinity). The widespread use of residential water softeners is also of concern, water softeners end up in wastewater streams and, ultimately, are discharged to receiving waters (Figure 2).

Southern California

IMPORTED WATER FROM THE Colorado River, which constitutes about 30% of the Los Angeles (LA) water supply, is both salinizing and becoming unreliable. The salinity of LA's three local water resources—stormwater, wastewater, and groundwater—is rising due to (1) salt importation (carried along with water from the Colorado River and Bay Delta), (2) dissolution of concrete (i.e., urban karst), (3) seawater intrusion (over-pumping of groundwater and sea level rise), and (4) water conservation activities that reduce wastewater flows and increase wastewater salinity. Thus, managing freshwater salinization in this region will require system-level co-management of imported water, stormwater, groundwater, and recycled water.

A National Research Agenda

IN 2018, WRF, AMERICAN WATER Works Association, Water Environment Federation, and the National Association of Clean Water Agencies initiated the exploratory effort, "Managing Impacts from Deicing Salt on Drinking Water Supplies: Research Needs and Project Concepts." The objectives were to identify critical knowledge gaps and research needs related to the impacts of deicing salts on water quality at the watershed scale, and to determine what communities can do to minimize salinization impacts on their water resources and drinking water supplies, especially in urban areas.

Building on this initial effort, and with financial support from the National Science Foundation, the authors of this paper hosted a workshop in January 2020 to develop a research agenda for reversing freshwater salinization. The workshop attendees, including 100 stakeholders from government, industry, and academia, deliberated and ultimately developed a shortlist of research questions that must be answered if we are to appropriately address freshwater salinization at the U.S. national scale. Their top question was: Can the sources of salt responsible for freshwater salinization in a particular region be identified, monitored, and curtailed?

"Predictability" was a common concern across various domains, from human behavior (Can we induce businesses and residents to be more conservative about their use of deicers on parking lots and driveways, and what is the "right amount" of deicer to use?), to hydrology (What are the hydrologic pathways by which salt moves through watersheds, and what are their timescales?), to ecology (How do the changing concentrations and compositions of salinized waters alter biological communities and ecosystem processes?), to engineering design (Are we unintentionally creating legacy salt pollution by adopting stormwater best management practices that transfer road salts to groundwater?).

Keeping in mind the goal of developing holistic, community-scale solutions, stakeholders also discussed unintended consequences and feedbacks.

WRF is currently working with a subset of the authors the project, "Catalyzing Stakeholder-Driven Solutions to Inland Freshwater Salinization" (VT, n.d.), supported by a National Science Foundation Growing Convergence Research grant. Experience gained and lessons learned from this research effort, which is focused on reversing freshwater salinization in northern Virginia, will be upscaled nationally and globally.

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