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Social-ecological-technological drivers of freshwater salinization in the Occoquan Reservoir, United States

Check for updates

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Freshwater salinization is an emerging and largely unregulated threat to drinking water security. We identify three dominant, seasonally distinct sources of rising sodium in a drinking water supply serving 1 million people: (1) road deicers, which elevate reservoir sodium in winter, with detectable impacts at watershed impervious cover as low as 3%; (2) reclaimed water, which increases sodium during summer low flows when dilution is minimal; and (3) the drinking water treatment plant (DWTP), which adds NaOH to neutralize acidity from coagulation and in-reservoir microbial processes. In this social-ecological-technological system (SETS), salinization is tied to population growth, impervious cover, sodium-rich waste streams, nitrogen management, reservoir biogeochemistry, and DWTP operations. Framing drinking water salinization as a SETS challenge integrates behavioral and biophysical drivers with engineering and governance responses, providing a framework for adaptation in One Water systems.

Salinization of drinking water is a pervasive and largely unregulated challenge in the United States and globally¹. Rising concentrations of chloride, sodium, and other dissolved salts have been documented in streams, lakes, reservoirs, and groundwater aquifers across diverse hydroclimatic and land-use settings². In many regions, these increases track with urbanization, expanding impervious cover, intensified road deicing, and wastewater discharges, while in others they are associated with interactions between climate variability, sea level rise, geogenic salt sources, and mining and energy extraction activities^{3–7}. Regardless of origin, the trajectory is clear: salinization is compromising the chemical integrity of freshwater resources upon which human societies depend¹.

Collectively, the impacts of drinking water salinization are experienced both acutely through taste and odor problems⁸, and chronically through long-term infrastructure corrosion⁹, human health issues¹⁰, and economic burdens on utilities and ratepayers¹¹. For example, elevated sodium ion concentrations can contribute to dietary sodium undermining clinical guidelines for individuals with hypertension and other cardiovascular

conditions^{12,13}, and at higher levels contributing to adverse outcomes such as pre-eclampsia¹⁴. Elevated chloride ion concentrations accelerate corrosion of distribution systems, mobilizing toxic metals, including lead, copper, and manganese^{15,16}. Other salts, including calcium, magnesium, and potassium, can alter drinking water hardness and pH buffering capacity, with implications for treatment efficiency and water quality stability¹⁷.

Unlike pathogens or many organic contaminants, salts are exceedingly difficult and expensive to remove once they reach drinking water treatment plants. Reverse osmosis and related desalination technologies can be effective¹¹, but they impose enormous costs on water utilities, increase energy consumption and greenhouse gas emissions, reduce the source water yield¹⁸, and generate brine waste streams that create additional disposal challenges³. Such technological “fixes” also risk creating maladaptive, inter-generational lock-ins, where short-term water quality gains come at the expense of long-term economic, environmental, and governance resilience¹⁹. A more sustainable and cost-effective pathway is to identify and mitigate the dominant salt sources before they enter drinking water supplies.

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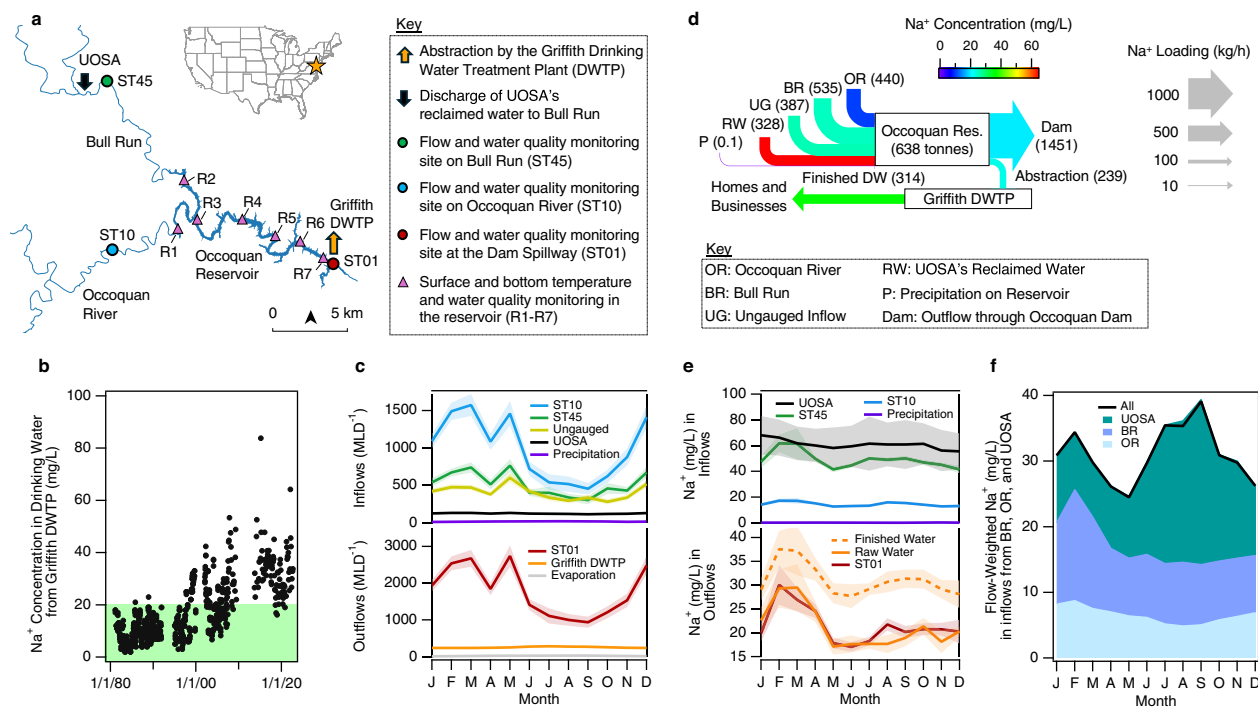


Fig. 1 | The Occoquan One Water system. **a** Occoquan Reservoir, its two primary tributaries (Bull Run and the Occoquan River), stream flow monitoring and sampling stations (ST45, ST10, ST01), and reservoir sampling stations (R1–R7). The Griffith Drinking Water Treatment Plant (DWTP) intake is located near the Occoquan Dam at monitoring station ST01. Reclaimed water from the Upper Occoquan Service Authority (UOSA) is discharged to Bull Run upstream of monitoring station ST45. **b** 40 years of Na⁺ concentrations in finished drinking water produced by the Griffith DWTP; green indicates concentrations below the EPA recommendation for a sodium-restricted diet. **c** Seasonal patterns of average monthly reservoir inflows (top panel) and outflows (bottom panel) in units of

megaliters per day (MLD⁻¹). **d** Average Na⁺ mass loading (size of arrows) and concentration (color) along flow paths leading to drinking water produced by the Griffith DWTP. **e** Seasonal patterns of average monthly Na⁺ concentrations measured in reservoir inflows (top panel) and outflows (bottom panel). **f** Flow-weighted Na⁺ concentration entering the reservoir from the two major tributaries (black curve), disaggregated by contributions from the Occoquan River (OR) watershed, Bull Run (BR) watershed upstream of UOSA, and UOSA's reclaimed water (UOSA). Results presented in c–f are based on flow and Na⁺ concentration measurements collected over an 11-year period, from January 1, 2010 to December 31, 2020. Shaded bands in c and e are the standard error of the mean.

The urgency of source control is magnified in the context of urban water systems that draw on a portfolio of source waters—including watershed inflows, stormwater runoff from cities and other impervious areas, and highly treated wastewater or ‘reclaimed water’—to improve reliability and sustainability^{20–23}. Although such One Water systems are often promoted as the future of resilient urban water systems^{24,25}, source diversification makes them especially vulnerable to salinization. Each source contributes a distinct salt fingerprint: deicers in urban runoff from regions with seasonal snow and ice, elevated sodium and chloride in reclaimed water and other wastewater discharges, and geogenic salts from the surrounding watershed²⁶. The overprinting of salt sources can push finished drinking water toward thresholds that compromise health, taste, and infrastructure³.

Further, the governance of One Water systems is typically distributed across multiple agencies, utilities, and jurisdictions that share overlapping responsibilities for water quality and supply. Such polycentric governance arrangements can enhance resilience by fostering local collaboration and experimentation²⁷, but they can also create challenges if poorly coordinated, with duplicative efforts in some areas and gaps in others²⁸. In such systems, three antecedents are particularly important for enabling productive polycentric governance^{29,30}: (1) robust monitoring and predictive capacity to anticipate system behavior; (2) shared understanding of the coupled social-ecological-technological feedbacks that shape outcomes; and (3) mechanisms for translating that understanding into collaborative decision-making and action.

Slowing, and ideally reversing, the salinization of One Water systems will therefore require recognizing that they are coupled social-ecological-technological systems (SETS), in which drinking-water outcomes emerge from interactions among governance institutions,

engineered infrastructure, and watershed ecological and biogeochemical processes^{19,31–34}. As a demonstration of this approach, in this study, we present a stakeholder-engaged analysis of rising sodium ion concentrations in finished drinking water sourced from the Occoquan Reservoir, a critical drinking water supply for up to 1 million people in Northern Virginia, USA^{35–37}. Consistent with the three antecedents outlined above, we analyze sodium sources and their seasonal dynamics, evaluate how SETS processes and feedbacks shape sodium inputs, and show how these insights are informing bottom-up governance. By integrating governance, ecological, and engineering analysis with stakeholder engagement, this study uncovers the drivers of drinking water salinization in the Occoquan Reservoir and demonstrates how framing the problem as a SETS challenge can guide collaborative pathways for managing cascading water quality challenges in One Water systems worldwide.

Occoquan One Water system

The Occoquan Reservoir is a quintessential One Water system, integrating inflows from natural tributaries, groundwater, urban runoff, and reclaimed water (Fig. 1a). On average, its two main tributaries—the Occoquan River and Bull Run—supply about 80% of inflows, with the remainder from rainfall on the reservoir surface and smaller ungauged sources around the perimeter. A substantial portion of Bull Run flow (about 19% on average) is reclaimed water from the Upper Occoquan Service Authority (UOSA), making this one of the earliest and largest indirect potable reuse (IPR) projects in the United States. UOSA employs a multi-barrier advanced treatment train that extends beyond conventional secondary treatment, incorporating biological nutrient removal (with seasonally adjusted denitrification to manage nitrate delivery), chemical phosphorus removal, media filtration, granular activated

carbon, and disinfection. At the downstream end of the reservoir, Fairfax Water's Griffith Drinking Water Treatment Plant (DWTP) withdraws raw water and applies advanced processes, including coagulation, sedimentation, ozonation, filtration, and disinfection before distributing finished water to retail and wholesale customers. Critically, neither UOSA nor Griffith employs desalination technologies such as reverse osmosis. Consequently, sodium ions introduced from raw sewage, deicer wash-off, watershed inflows, or treatment additions persist through both facilities and accumulate in the finished drinking water, as evidenced by the rising Na^+ concentrations in the finished drinking water over the past 40 years (Fig. 1b).

Tributary inflows and reservoir outflows both show pronounced seasonality, with higher flows in winter and reduced flows in August through September when watershed evapotranspiration peaks (Fig. 1c). On a day-to-day basis, inflows can fluctuate by more than two orders of magnitude between baseflow and storm events. Against this variability, UOSA's reclaimed water provides a stable baseline: while only 6% of the average inflow to the reservoir from all sources, it is occasionally the largest source of water entering the reservoir during extended dry periods, underscoring the stabilizing role of IPR in maintaining reservoir supplies.

When this IPR system was conceived and constructed in the early 1970s, deliberately blending reclaimed water with a drinking water reservoir was relatively untested³⁸. To manage the potential ecological and human health risks, Virginia adopted the Occoquan Policy³⁹, creating a polycentric governance framework linking regulators, utilities, and scientists³⁰. A cornerstone of the Policy was the establishment of the Occoquan Watershed Monitoring Program, administered by the Occoquan Watershed Monitoring Laboratory (OWML), which has provided continuous, independent water supply and quality surveillance for more than four decades. This long-term monitoring has underpinned adaptive governance by ensuring that decisions are grounded in transparent data and has been critical in controlling pollutants, such as phosphorus and nitrogen, sustaining the reservoir through multiple water quality challenges⁴⁰.

Today, the system is increasingly challenged by pollutants that fall outside traditional regulatory frameworks, including sodium, which is not regulated under either the U.S. Clean Water Act or Safe Drinking Water Act. The U.S. Environmental Protection Agency (EPA) has issued a health advisory at 20 mg/L Na^+ in drinking water for individuals on a severely restricted sodium diet⁴¹, a threshold now routinely exceeded in finished drinking water from the Griffith DWTP (green region, Fig. 1b). The US EPA has also set taste thresholds for sodium in drinking water of between 30 and 60 mg/L⁸. The maximum sodium concentrations measured in Griffith's finished drinking water (ca. 60–80 mg/L) are at the high end of those reported in drinking water across the United States⁴². Further, the persistent upward trend underscores the urgency of proactive interventions before concentrations necessitate costly and potentially maladaptive end-of-pipe solutions³.

This combination of factors—long-term monitoring, a governance framework that institutionalized collaboration, rising but still manageable sodium levels, and the opportunity to act before costly and potentially maladaptive end-of-pipe solutions are required—positions the Occoquan Reservoir as an ideal testbed for examining salinization as an SETS challenge.

Results and discussion

Stakeholder engagement and system predictability

At the outset of this project, we asked practitioners engaged in the day-to-day management of the Occoquan Reservoir to identify and rank information needs for sodium management²⁸. All 40 respondents rated system predictability—defined as “understanding of salt sources, fate, transport, and dynamics in the watershed, sewershed, and reservoir”—as very important or extremely important (Supplementary Note 1).

Guided by this input, the research team embarked on a 5-year collaboration with stakeholders, involving six multi-agency workshops and extensive one-on-one discussions, to ensure that local knowledge and practitioner expertise directly shaped the scientific analyses. Together, we

defined the engineered and natural flow paths that deliver sodium to the reservoir, compiled and synthesized diverse monitoring datasets, and co-interpreted results to maximize their salience, credibility, and legitimacy (Supplementary Notes 2 and 3)^{43–45}.

This collaborative process revealed three primary sodium sources in finished drinking water from the Occoquan Reservoir: (1) streamflow and urban runoff from tributaries; (2) UOSA's reclaimed water; and (3) treatment processes at Fairfax Water's Griffith DWTP. On average, 1.7 metric tonnes of sodium enter and leave the reservoir each hour (Fig. 1d). The largest contributions come from Bull Run (32%), the Occoquan River (26%), and ungauged inflows, such as groundwater and smaller tributaries (23%). Although reclaimed water accounts for a smaller share of the total sodium mass (19%), it has the highest average concentration (63 mg/L), nearly three times higher than the average sodium concentration in water abstracted from the reservoir by the Griffith DWTP (23 mg/L). As the water undergoes treatment at Griffith, Na^+ concentrations increase by around 43%, rising on average from 23 to 33 mg/L. This last finding, which caught many stakeholders by surprise, is explored in the section “Contribution of drinking water treatment”.

To probe seasonal dynamics, we used two complementary approaches. First, we examined the seasonal patterns of Na^+ concentrations in individual reservoir inflows and outflows (Fig. 1e). UOSA's reclaimed water is consistently elevated (60–70 mg L⁻¹) with little seasonal variation. Monthly average Na^+ concentrations at ST45 are somewhat lower and exhibit two distinct seasonal peaks—one in February–March and another in July–October. These dual peaks are also evident downstream at Station ST01 and in Griffith's raw water intake, and are especially pronounced in finished drinking water, which averages about 10 mg L⁻¹ higher than the intake (bottom panel).

Second, to quantify the relative contribution of upstream sources to the dual peak pattern evident at the drinking water intake, we calculated the monthly flow-weighted Na^+ concentrations of three major sources of sodium to the reservoir: Occoquan River, Bull Run upstream of UOSA, and UOSA's reclaimed water (Fig. 1f). The results indicate that the winter peak is driven primarily by watershed inputs (most likely associated with winter deicer use, see section “Contribution of winter deicing”), while the summer peak reflects reduced dilution of UOSA's relatively constant, high-sodium discharge, by reduced watershed inflows (Fig. 1c).

Together, these results enhance system predictability by identifying the dominant sources of Na^+ in the reservoir, documenting a dual peak seasonal pattern in both the reservoir and Griffith's finished drinking water, and tracing those peaks to their primary drivers—episodic watershed inputs from deicers in winter and reduced dilution of reclaimed water in summer. Next, we explore the SETS challenges associated with the three main sources of sodium ions in the finished drinking water produced by Griffith, including winter deicer use, reclaimed water, and water treatment processes.

Contribution of winter deicing

A primary source of sodium in tributary flows to the reservoir is the application of deicers on impervious surfaces in the watershed. Supporting evidence includes: (1) strong spatial and temporal correlations between impervious cover and average stream sodium concentrations in the winter; and (2) extreme spikes in sodium during winter weather conditions, especially in more urbanized sub-watersheds.

From 2010 to 2021, outflows from the two more developed sub-watersheds (Cub Run and Middle Broad Run, ST50 and ST30, Fig. 2a) exhibited higher minimum, mode, and extreme Na^+ concentrations than those draining less developed areas (Fig. 2b, upper panel). Na^+ concentrations in outflow from the least developed sub-watersheds (e.g., Upper Broad Run, ST70, Fig. 2a) indicate that the geogenic baseline for this region is around 10 mg/L. Over the past four decades, the bulk salinity in outflow from Cub Run (ST50) has risen in parallel with impervious cover, which increased from ~14% in the mid-1980s to >30% today (Fig. 2c, upper panel). Much of this added salt is concentrated in the winter months (Fig. 2b,c,

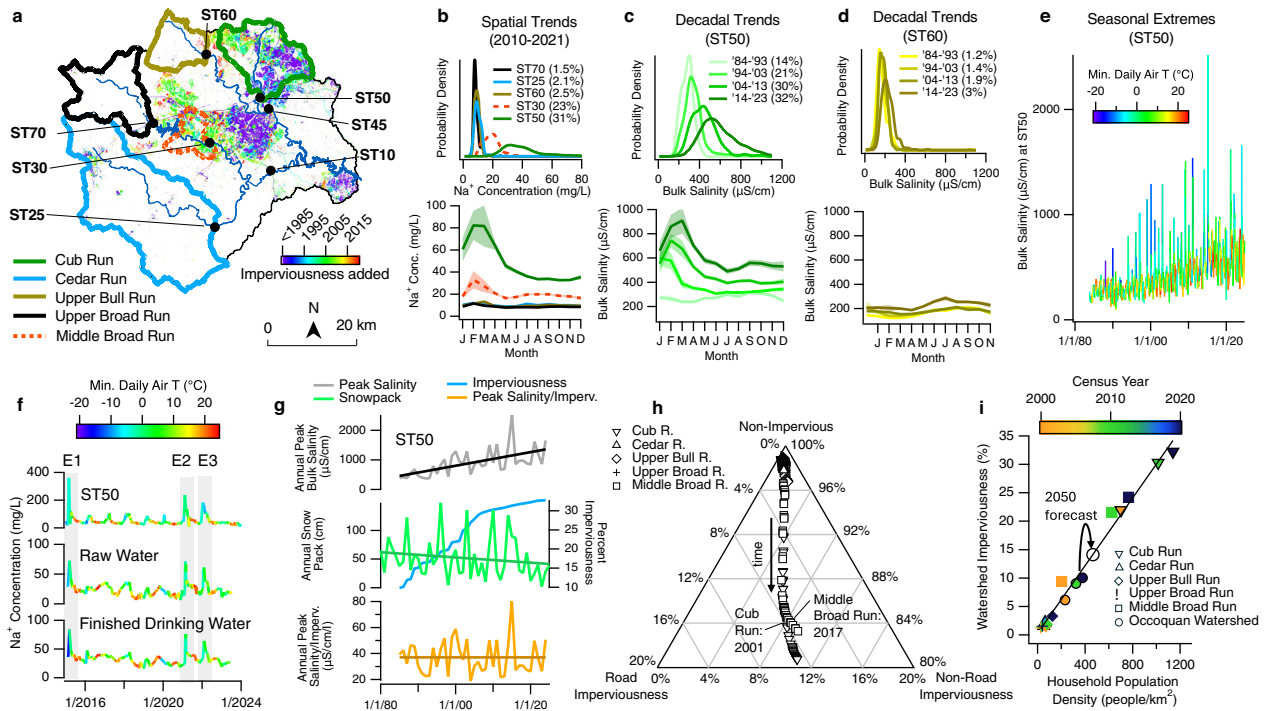


Fig. 2 | Relationship between watershed imperviousness and stream, reservoir, and drinking water salinity. **a** Timing of impervious surface addition in the Occoquan Watershed (color) with delineated sub-watersheds for five stream sampling stations (ST25, ST30, ST50, ST60, ST70). **b** Probability distributions of Na⁺ concentrations (top panel) and seasonal trends (bottom panel) across sub-watersheds from 2010 to 2020. **c** and **d** Probability distributions of bulk salinity (specific conductance) (top panel) and seasonal trends (bottom panel) over four decades at ST50 (**c**) and ST60 (**d**); parentheses in (**b**)–(**d**) indicate average sub-watershed impervious cover. **e** Seasonal extremes in bulk salinity at ST50 have increased over the past 40 years despite overall warming (see color scale). **f** Na⁺ spikes at ST50 align with those in Griffith’s raw and finished drinking water (events E1, E2, E3). **g** Annual extremes in bulk salinity at ST50 have risen at 23 ± 5.0 µS/cm/year (gray, top), concurrent with increasing impervious area in the Cub Run sub-watershed (blue, middle) and declining annual snowpack at -0.46 ± 0.41 cm/year

(green, middle). Normalizing bulk salinity extremes by impervious fraction removes the long-term trend (orange, bottom); the intercept corresponds to an increase in bulk salinity extremes of 37 ± 8.2 µS/cm for every 1% increase in impervious area. **h** Ternary diagram showing the increase in imperviousness across the five sub-watersheds is equally partitioned between roads and other non-road urban areas until an average imperviousness fraction of around 16%, when more of the added imperviousness is associated with non-road urban areas; this transition occurs in 2001 for Cub Run and 2017 for Middle Broad Run. **i** Impervious fraction scales linearly with household population density across all sub-sheds and census years (2000, 2010, 2020), corresponding to a 3% increase for every additional 100 people/km² ($R^2 = 0.99$, black line). Given projected population growth, impervious cover in the Occoquan Watershed is expected to reach 14.1% by 2050 (curved arrow). Shaded bands in the bottom graphs of **b**–**d** are the standard error of the mean.

lower panels). By contrast, sodium concentrations in outflow from Upper Broad Run (ST60), a nearby but sparsely developed watershed, showed little change until the past decade, when a modest salinity increase coincided with impervious cover rising from just 1.9% to 3%, suggesting that even minimal development can initiate salinization (Fig. 2d, top panel). This added salinity appears to be concentrated in the summer (Fig. 2d, lower panel), consistent with deicers reaching the stream via longer subsurface flow pathways in this largely undeveloped watershed⁴⁶.

Deicers also generate short-lived but extreme spikes in stream salinity that propagate through the watershed and reservoir into finished drinking water. At Cub Run (ST50), the magnitude of winter Na⁺ extremes has risen steadily over the last four decades, with peak bulk salinity values now frequently exceeding 1500 µS/cm (≈150 mg/L Na⁺; Fig. 2e, Supplementary Note 4). Three representative events (E1–E3; Fig. 2f) illustrate how spikes in winter sodium ion concentrations at ST50 are also evident in raw water at Griffith’s intake, and persist through treatment into the finished drinking water supply (see also Supplementary Note 5).

To identify drivers of these salinity spikes, we extracted annual maxima from the 40 years of weekly bulk salinity measured at ST50 (gray curve, Fig. 2g). Despite a regional warming trend (fewer deep blue spikes, Fig. 2e) and declining snowpack (green curve, Fig. 2g), the magnitude of these annual salinity maxima has increased at a rate of 23 ± 5 µS/cm per year (black line, Fig. 2g). This increase closely tracks rising impervious cover in the Cub Run watershed (blue curve, Fig. 2g). Indeed, when the annual Na⁺

maxima are normalized by impervious fraction, the resulting ratio shows variability but no significant trend (i.e., the slope is zero within error, orange curve, Fig. 2g), implying that salinity extremes scale linearly with watershed imperviousness.

Across all five sub-watersheds and over the period for which land cover data are available (1985–2024)⁴⁷, impervious cover is divided about equally between road networks and non-road urban surfaces, including rooftops, driveways, sidewalks, and parking lots (Fig. 2h). However, once the average impervious fraction exceeds 16% (around 2001 for Cub Run and 2017 for Middle Broad Run) new imperviousness shifts markedly toward non-road surfaces (Fig. 2h). This pattern is consistent with urban infill, where expansion occurs within existing road networks rather than through new road construction⁴⁸. The shift has important management implications: while roads are typically maintained in winter by professional operators (e.g., Departments of Transportation), non-road surfaces are often treated by private contractors or property owners, who may apply salt less efficiently. Targeting these users through salt education, certification programs⁴⁹, and the deployment of green infrastructure for salt capture and reuse⁵⁰ could be especially important for watersheds where the impervious cover exceeds ca. 15%.

Impervious cover scales linearly with household population density across all five sub-watersheds and over the three census decades available (2000, 2010, 2020), increasing by 3% for every additional 100 people/km² (Fig. 2i). Therefore, with population in the Occoquan watershed projected to

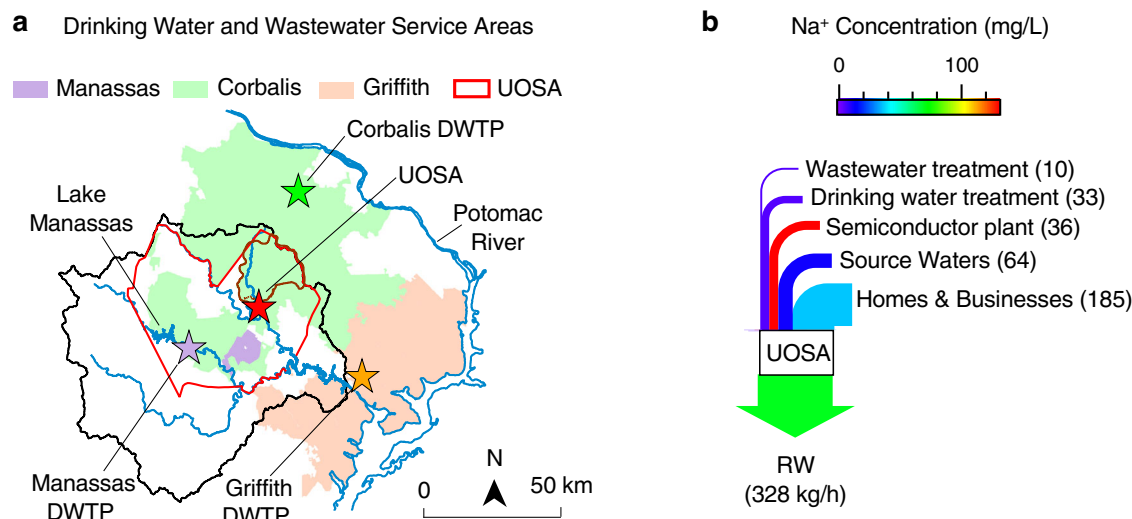


Fig. 3 | Sources of sodium along flow paths leading to reclaimed water. **a** Service areas for drinking water and wastewater infrastructure in the Occoquan Watershed. The City of Manassas, Corbalis, and Griffith DWTPs source their raw water from Lake Manassas, the Potomac River, the Occoquan Reservoir, respectively. The

UOSA water reclamation plant's service area (red border) includes homes and businesses that receive drinking water from the Corbalis and Manassas DWTPs. **b** Average Na⁺ mass loading (size of arrows, in units of kg per hour) and concentration (color, units mg/L), along flow paths leading to UOSA's reclaimed water.

grow from 591,000 today to 712,200 by 2050⁵¹, we estimate that watershed imperviousness will rise from 12% to 14% (curved arrow, Fig. 2i). This additional imperviousness will drive a proportional increase in annual Na⁺ extremes in Griffith's finished drinking water by mid-century, which under business-as-usual conditions could exceed 100 mg/L, or five times EPA's 20 mg/L low-sodium diet health advisory.

Contribution of water reclamation

Sodium ions also enter the Occoquan Reservoir through reclaimed water produced by UOSA ("RW" in Fig. 1d). The reclaimed water originates as sewage, which undergoes a high degree of treatment by UOSA before being discharged to Bull Run. In turn, the sewage originates from raw water supplied to two regional DWTPs: the Corbalis DWTP, which draws from the Potomac River, and the City of Manassas DWTP, which draws from Lake Manassas (Fig. 3a). Sodium is present in these raw source waters and is further introduced during drinking water treatment at both facilities. The finished drinking water is then distributed to homes and businesses, where additional sodium is added through human excretion of dietary sodium (via urine and feces)⁵² as well as through the down-drain disposal of sodium-rich products, including laundry detergents^{3,53} and water softeners⁵⁴.

Over the 11-year study period, 56% of the sodium mass in UOSA's reclaimed water originated from homes and businesses within its service area (Fig. 3b) (see the "Methods" section). Of that portion, ~27% is attributable to human excretion (via urine and feces), while the remaining 73% is likely from the down-drain disposal of sodium-rich products, including laundry detergents^{3,53} and water softeners⁵⁴, in homes and businesses in UOSA's service area. We estimated the contribution from human excretion based on an average dietary Na⁺ intake of 3.4 g per person per day^{55–57} and a UOSA service population of 351,906. Additional sources of sodium include the two source waters (Potomac River and Lake Manassas, 20%), a permitted discharge from a large semiconductor manufacturing facility (11%), and chemicals added during drinking water (10%) and wastewater (3%) treatment processes.

Contribution of drinking water treatment

Next we evaluate the drivers of sodium addition by the Griffith DWTP (Fig. 1d). Several treatment chemicals used at the Griffith DWTP are sodium salts, including sodium hydroxide (NaOH, a base), sodium hypochlorite (NaOCl, a disinfectant), and sodium bisulfite (NaHSO₃, a reductant) (Fig. 4a). Over the 11-year study period (2010–2021), these chemicals

increased sodium concentrations in finished drinking water by ~4–6 mg/L from NaOH, 2 mg/L from NaOCl, and <0.1 mg/L from NaHSO₃ (Fig. 4b). The largest contributor, sodium hydroxide, is added primarily to raise the pH of finished water in order to reduce corrosion in the distribution system and comply with federal Lead and Copper Rule requirements⁵⁸. Notably, NaOH addition follows a strong seasonal pattern, with peak usage in July–September.

Carbonate buffer calculations closely reproduce the observed seasonal variation in NaOH addition (Fig. 4c; see the "Methods" section). From these calculations we infer that, on average, about half of the NaOH is needed to neutralize acidity generated within the treatment plant by hydrolysis of the coagulant polyaluminum chloride (PACl; arrow "1" in Fig. 4a), while the other half is needed to neutralize acidity in the raw water (arrow "2" in Fig. 4a) (Fig. 4d). The seasonal peak in NaOH addition occurs in late summer, when raw intake water exhibits low pH (<6.9) and high alkalinity (>60 mg/L) (open circle on solid black curve, Fig. 4e)—a combination that requires more sodium hydroxide to raise the finished water pH, because higher alkalinity increases pH buffering capacity⁵⁹. Although the Griffith intake structure can draw from multiple depths, the mid-level intake, which is frequently used during summer, partially entrains water below the thermocline where pH is low, and alkalinity is high (compare the solid, dashed, and dot-dashed curves in Fig. 4e).

The above results provide a proximate explanation for the seasonal variation in NaOH addition. A more complete understanding requires consideration of how upstream nitrogen management and ecological processes shape the chemistry of raw water entering the Griffith DWTP, particularly its low pH and high alkalinity in summer. We examine these two factors in turn.

First, the low pH. In summer, the Occoquan Reservoir thermally stratifies, with warm surface waters overlaying a colder hypolimnion (blue box, Fig. 4f). Stratification coincides with surface algal blooms (Fig. 4g) and, at depth, elevated concentrations of dissolved organic carbon (Fig. 4h) and low concentrations of dissolved oxygen (Fig. 4i). These limnological and biogeochemical changes drive a seasonal divergence in surface and bottom pH, rising at the surface and falling at depth (Fig. 4j)—a pattern consistent with CO₂ uptake by photosynthesis in the epilimnion and CO₂ production by heterotrophic respiration, and possibly organic acid production by fermentation, in the hypolimnion⁶⁰. Thus, the lower summertime pH in bottom waters near the Griffith intake reflects broader-scale limnological and ecological processes operating throughout the reservoir.

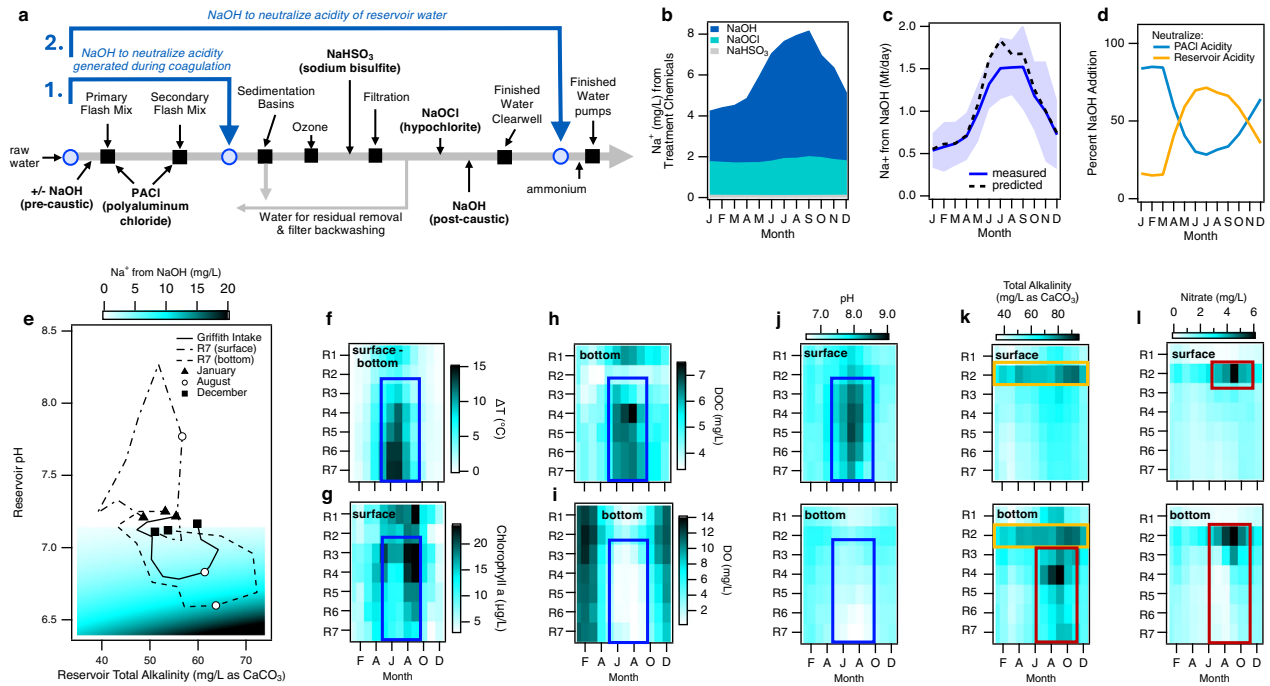


Fig. 4 | Sources and ecological drivers of Na^+ added by the Griffith DWTP.
a DWTP treatment processes include coagulation (with polyaluminum chloride, PACl), sedimentation, ozonation, filtration, and disinfection. NaOH is added at the beginning (pre-caustic) and end (post-caustic) of the treatment train. Blue circles denote locations where pH and alkalinity are measured on a near-hourly basis.
b Monthly-average Na^+ concentration added by the three principle sodium-containing chemicals used during water treatment. **c** Model-predicted (black dashed line) and measured (blue solid line, blue shading is ± 1 s.d.) monthly average Na^+ mass added to finished drinking water from NaOH. **d** Model-predictions for the percent NaOH added to neutralize acidity generated during coagulation (Step 1 in

(a) and reservoir acidity (Step 2 in (a)). **e** Monthly-average pH and alkalinity in Griffith raw water (solid curve) compared to monthly average pH and alkalinity measured at reservoir station R7, near the Griffith intake (see Fig. 1a) and model-predicted NaOH (reported here as equivalent Na^+ concentrations) needed to neutralize reservoir acidity (heatmap). **f–l** Monthly-average measurements at reservoir stations R1–R7 of: **f** surface minus bottom temperatures, ΔT ; **g** surface Chlorophyll *a* concentration; **h** bottom dissolved organic carbon (DOC) concentration; **i** bottom dissolved oxygen (DO) concentration; **j** surface and bottom pH; **k** surface and bottom alkalinity; and **l** surface and bottom nitrate concentration.

Next, the high alkalinity. While some alkalinity is imported into the reservoir from UOSA and tributary watersheds—particularly along the Bull Run arm at station R2 (yellow box, Fig. 4k)—a “hot spot and hot moment” of alkalinity generation⁶¹ is also evident in the bottom waters of the reservoir near station R4 during July through September (red box, bottom panel, Fig. 4k). A likely explanation centers on UOSA’s long-standing practice of increasing nitrate concentrations in its reclaimed water during summer months. This practice is intentionally designed to improve reservoir water quality by providing an electron acceptor for microbial respiration, thereby limiting anoxia and the associated release of phosphorus and metals from sediments during stratification^{40,62}.

As the extra nitrate from UOSA enters the oxygen-depleted bottom waters of the reservoir, nitrate concentrations progressively decrease while alkalinity increases (compare red boxes in bottom panels of Fig. 4k, l). This pattern is consistent with denitrification, a microbially mediated process that converts nitrate to nitrogen gas while simultaneously generating alkalinity under low-oxygen conditions⁶³. Station R4 emerges as a hot spot for these processes because Ryan’s Dam, an old decommissioned structure now fully submerged at this location, provides ideal conditions for denitrification by trapping organic matter (top panel, Fig. 4h) and increasing the residence time of hypolimnetic water⁶¹. By late fall, the resulting alkalinity plume extends along the bottom of the reservoir for >5 km, from station R4 to station R7 (bottom panel, Fig. 4k), where it is entrained by the Griffith intake.

These findings demonstrate the system-of-systems⁶⁴ nature of this SETS, in which upstream nitrogen management decisions, limnological processes, in-reservoir biogeochemistry, and downstream treatment operations are tightly coupled, including: (1) the influx of alkalinity from tributary watersheds, particularly Bull Run; (2) UOSA’s summer

practice of increasing nitrate concentrations in reclaimed water to mitigate hypolimnetic anoxia; (3) physical transport processes that direct nitrate-enriched water into the oxygen-depleted bottom layers of the reservoir; (4) in-reservoir denitrification, which removes nitrate and generates alkalinity; (5) microbial respiration in the hypolimnion, which consumes oxygen and lowers pH; (6) Griffith’s intake, which partially entrains water from below the thermocline in the summer where alkalinity is high and pH is low; and (7) the utility’s operational response—adding NaOH to meet corrosion control goals and comply with federal lead and copper regulations.

Governance of One Water SETS

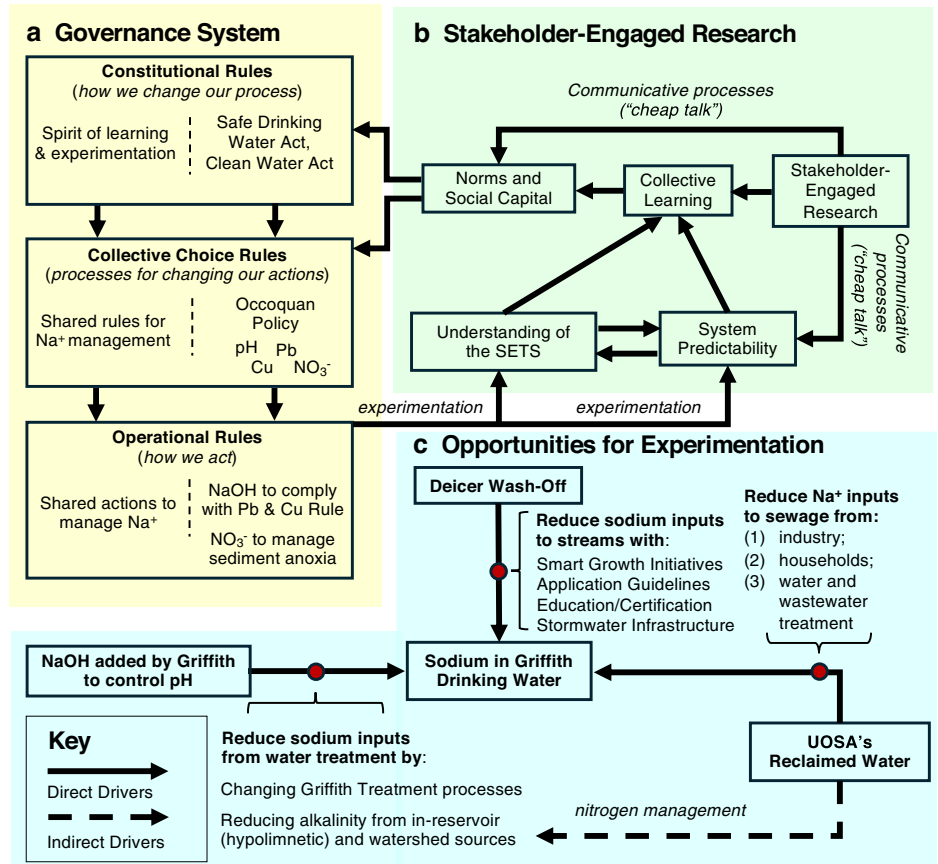
Polycentric management of water quality challenges in complex One Water systems, like the Occoquan Reservoir, can be conceptualized as a set of nested rules-in-use that interact across scales to structure how decisions are made and adapted (Fig. 5a)^{27,29}.

Operational rules govern day-to-day actions within the resource system. Examples include UOSA’s practice of discharging more nitrate in the summer to manage reservoir anoxia, and Griffith’s addition of NaOH to finished drinking water to comply with the federal Lead and Copper Rule (right-hand side of bottom box, Fig. 5a).

Collective-choice rules establish processes for modifying those operational actions. In the Occoquan system, these are formalized through the Occoquan Policy, a quasi-regulatory governance system codified in the Virginia Administrative Code (§9 VAC 25-410), which empowers the Occoquan Watershed Monitoring Subcommittee to oversee UOSA’s operational practices (right-hand side of middle box, Fig. 5a).

Constitutional rules define how collective-choice processes themselves can be changed. While the Occoquan Policy predates the U.S. Clean Water

Fig. 5 | Catalyzing collaborative rule-making in One Water SETS. **a** Nested rules-in-use at the operational, collective-choice, and constitutional levels. **b** Stakeholder-engaged research improves system predictability and understanding of the SETS, and strengthens norms and social capital by fostering “cheap talk,” trust, shared expectations, and cooperation among resource users. **c** Ongoing efforts to reduce Na⁺ concentrations in the finished drinking water produced from the Occoquan Reservoir, including inputs from deicer wash-off, UOSA’s reclaimed water, and the Griffith DWTP.



and Safe Drinking Water Acts, it is now shaped and constrained by those federal mandates (right-hand side of top box, Fig. 5a).

Together, these nested rules-in-use structure the management of regulated contaminants in the Occoquan Reservoir and at the Griffith DWTP. By contrast, rules for managing sodium, a currently unregulated contaminant, have evolved pragmatically, often subordinated to compliance with other mandates. However, as demonstrated by Nobel Laureate Elinor Ostrom²⁹, non-regulatory collaborative approaches can also be built across all three governance levels, grounded in shared norms and a spirit of experimentation (left-hand side of Fig. 5a).

Our stakeholder-engaged research is helping to catalyze such collaborative rule-making for sodium in the Occoquan Reservoir by (Fig. 5b): (1) improving system predictability and stakeholder understanding of the SETS; (2) fostering collective learning and what Ostrom referred to as “cheap talk”—low-cost communication channels that facilitate shared sense-making²⁷; and (3) strengthening norms, trust, and social capital. Tangible examples include (Fig. 5c):

- Recognition of alkalinity-sodium tradeoffs in the Griffith-UOSA system has prompted Fairfax Water to incorporate sodium considerations into treatment planning, including real-time modeling of water quality with intake depth and evaluation of lime substitution for NaOH.
- Evidence that households and businesses dominate sodium loads in reclaimed water has spurred discussions with UOSA and the local jurisdictions about consumer product policies (e.g., phasing out sodium-rich powdered laundry detergents⁵³) and launching social marketing campaigns to encourage low-sodium alternatives.
- The proportional relationship between impervious fraction and extremes in stream Na⁺ concentrations—together with projected growth in impervious cover in the Occoquan watershed—has motivated follow-up field studies to identify winter maintenance best practices across diverse urban land uses.

- Finally, population in the Occoquan Watershed has more than tripled over the past four decades, from 138,000 in 1980 to 591,000 today, and continued growth—including expanding investment in novel land uses with substantial development footprints, such as data centers⁶⁵, which may not conform to the historical relationship between population growth, imperviousness, and deicer wash-off rates—is likely. Building on our findings, a local NGO, the Prince William Conservation Alliance, has launched a community-driven sustainable growth framework that centers on drinking water protection—an emphasis absent from traditional smart growth models^{66,67}. Balancing future growth in population and associated imperviousness with the protection of downstream drinking water quality will remain a defining challenge for the region.

Conclusions

The growing challenges facing regulatory approaches to environmental protection⁶⁸ heighten the urgency for self-organized forms of adaptive governance^{19,69}. Drinking water salinization exemplifies this need: it is not only a biophysical process but a Social–Ecological–Technological systems challenge, in which outcomes emerge from the interplay of governance institutions, ecosystem processes, and engineered infrastructure.

Our work in the Occoquan Reservoir demonstrates how stakeholder-engaged research can help foster collective action around emerging water quality threats that fall outside the reach of conventional regulation. By linking sodium sources to land cover change, product choices, reclaimed water practices, biogeochemical, limnological, and ecological processes, and treatment operations, and by embedding these insights within ongoing governance processes, we illustrate how stakeholder-engaged research can foster trust, shared understanding, and system predictability.

Framing drinking water salinization as a SETS challenge and addressing it through stakeholder-engaged research offers a scalable pathway for stakeholder-driven solutions to salinization and, more broadly, to the many

rapidly evolving water quality challenges confronting drinking water systems worldwide.

Methods

Stakeholder engagement

At the start of the 5-year study, the research team held a virtual workshop on May 24, 2021, to identify long-term goals and information needs for managing sodium in the Occoquan Reservoir. The workshop was attended by 40 stakeholders representing federal and state regulators, utilities, local governments, industry, and NGOs. Stakeholders submitted written input in advance, which was synthesized into nine candidate goals and nine information needs. During facilitated breakout discussions, participants refined these into 13 final goals and 16 information needs. Stakeholders then scored each item's importance in a real-time survey using a 5-point Likert scale. Consensus among respondents was quantified using the Tastle–Wierman metric⁷⁰, which ranges from 0 (no agreement) to 1 (complete consensus). Informed consent was obtained from all participants. Additional details are provided in Supplementary Method 1.

Water and sodium mass balance over the reservoir

In this region, storm events can increase streamflow by several orders of magnitude, and stream Na^+ concentrations are often inversely correlated with flow³. To obtain unbiased estimates of sodium mass loading rates that explicitly account for the anti-correlation between Na^+ concentrations and flow⁷¹, we first constructed synthetic hourly or daily time series of Na^+ concentrations for all reservoir inflows and outflows using regression models trained on Na^+ concentration measurements ($N = 370$ at ST10, 296 at ST45, 68 for reclaimed water, 160 at ST01, 105 at DWTP raw water, and 85 at DWTP finished water) and environmental covariates identified through stakeholder input. For each site, the most parsimonious MLR model was selected by Bayesian Information Criterion (BIC) ranking from a population of models that included all possible covariate combinations; model fit was further evaluated against withheld data to assess predictive accuracy. Hourly or daily mass loading rates were then calculated by multiplying the synthetic MLR-predicted concentrations by hourly or daily measured flow. The resulting Na^+ mass loading rates (kg/h) were averaged over the 11-year study period, from January 1, 2010, to December 31, 2020, to generate the mean values reported (thickness of arrows in Fig. 1d). Flow-weighted Na^+ concentrations were calculated as the ratio of the average mass loading rate and the average flow over the same period (color of arrows in Fig. 1d). All measurements were carried out by accredited laboratories. Additional details are provided in Supplementary Methods 2–4.

Stream salinity trends

To assess spatial and temporal patterns in stream salinity, we analyzed sodium concentrations and specific conductance measurements in stream outflows from five sub-watersheds within the overall watershed draining to the Occoquan Reservoir. Spatial patterns were assessed by comparing, over the 11-year study period described above, stream Na^+ concentrations measured in outflow from five sub-watersheds with contrasting levels of average impervious cover (ranging from 1.5% to 31%). Temporal trends were evaluated using four decades (1983–2022) of specific conductance measured in stream outflow from Cub Run (ST50), a sub-watershed that experienced substantial development over the 40-year period, and the adjacent Upper Bull Run (ST60), which remained relatively undeveloped over the same period. Probability density functions (PDFs) were constructed from these data using the SmoothKernelDistribution function in Mathematica (Wolfram, v 14.1). All measurements were carried out by accredited laboratories. Additional details are provided in Supplementary Method 5.

Watershed imperviousness and population estimates

Temporal changes in land cover were quantified using publicly available geospatial data. Impervious surface metrics were derived from the Annual National Land Cover Database Product Suite⁴⁷. We calculated the total

percent impervious area for each available year (using “FctImp” raster) and further disaggregated that into contributions from roads and non-road urban surfaces (using “ImpDsc” raster) in the R programming environment (packages *raster*, *sf*). Watershed population estimates for 2000, 2010, and 2020 were derived from U.S. Decennial Census data at the block group level using the R-package *tidycensus*. An areal interpolation method was used to apportion the population of census units to the precise sub-watershed boundary.

Sources of sodium in reclaimed water

To estimate the contribution of various sources to sodium loads in reclaimed water discharged to Bull Run, we decomposed the total measured mass loading (328 kg/h) into five categories: (1) sodium in the original source waters for drinking water (Potomac River and Lake Manassas); (2) sodium added during drinking water treatment; (3) sodium added during wastewater treatment; (4) sodium discharged by a semiconductor manufacturing facility; and (5) sodium added by other homes and businesses. Source water contributions were estimated from flow-weighted averages of reported Na^+ concentrations and the relative proportion of flow originating from each source. Sodium added during drinking and wastewater treatment was based on measured increases in Na^+ concentration between raw and finished water, combined with estimated flows. Sodium loads from the semiconductor manufacturing facility were based on self-reported daily discharge volumes and concentrations, adjusted to remove the Na^+ attributable to the incoming drinking water. Sodium from homes and businesses was estimated by difference. All measurements were carried out by accredited laboratories. Additional details are provided in Supplementary Method 6.

Estimating NaOH demand in drinking water treatment

To identify and quantify the sources of acidity that must be neutralized by sodium hydroxide (NaOH) addition at Fairfax Water's Griffith Drinking Water Treatment Plant (DWTP), we used carbonate buffer calculations to distinguish between two additive sources: (1) acidity generated by hydrolysis of polyaluminum chloride (PACl) during coagulation; and (2) acidity in the raw water from the Occoquan Reservoir. The first was estimated from the observed drop in total alkalinity across the coagulation step, adjusted for pre-caustic dosing and converted to an equivalent NaOH demand.

The second was estimated using the Henderson–Hasselbalch equation⁶⁰ to compute the NaOH dose required to shift the pH of the raw water—given its measured pH, temperature, and alkalinity—to the observed pH of the finished water. This calculation accounted for seasonal variation in carbonate equilibria by using temperature-dependent acid dissociation constants and assuming conservation of total inorganic carbon. Monthly averages of raw water temperature, pH, and alkalinity were used to estimate carbonic acid and bicarbonate concentrations, which in turn were used to solve for the NaOH dose needed to reach finished water pH. Predicted NaOH demand was compared to operational dosing records over the 11-year study period. Full derivations, assumptions, and governing equations are provided in Supplementary Method 7.

Reservoir water quality monitoring

Reservoir water quality was monitored weekly from January 2010 through December 2020 at seven stations (R1–R7) using standardized field and laboratory protocols. Depth profiles of temperature, pH, and dissolved oxygen were measured with a calibrated multi-parameter sonde, and surface and bottom values were extracted for analysis. Surface water was collected directly into pre-rinsed bottles, while bottom samples were retrieved using a Kemmerer sampler. At each site, chlorophyll *a* was measured in filtered surface samples by fluorometry, following pigment preservation and storage protocols.

Subsamples from surface and bottom waters were analyzed for sodium, nitrate/nitrite, dissolved organic carbon (DOC), and total alkalinity. Sodium was measured by ion chromatography, nitrate/nitrite by autoanalyzer, and DOC by high-temperature catalytic oxidation, all according to Standard

Methods. Alkalinity was measured in the field via titration. All analyses were conducted by Virginia Tech's Occoquan Watershed Monitoring Laboratory under VELAP-accredited protocols. Monthly averages of these variables were used to produce the heatmaps in Fig. 4e–i. Additional details are provided in Supplementary Method 8.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All biophysical and de-identified human subjects research data can be found at the following archive: <https://doi.org/10.4211/hs.98063d3cf62844cb966b2f461a47b5f2>. Ethical approval for human subjects research was granted by Virginia Polytechnic Institute and State University's Institutional Review Board (HS #20-648).

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Author contributions

Stanley B. Grant conceived the study, developed the methodology, conducted formal analysis, acquired funding, and wrote the original manuscript draft. Shantanu V. Bhide conceived the study, developed the methodology, conducted formal analysis, and contributed to writing the original draft. Anne Spiesman contributed text and assisted with data collection. Shalini Misra contributed text and assisted with funding acquisition. Megan A. Rippy contributed text, assisted with data analysis, and assisted with funding acquisition. Christopher A. Galik contributed text. Thomas A. Birkland contributed text and assisted with funding acquisition. Todd Schenk contributed text and assisted with funding acquisition. Sujoy S. Kaushal assisted with funding acquisition. Peter Vikesland contributed to funding acquisition. William Knocke conducted a formal analysis. Admin Husic conducted a formal analysis. Harold Post contributed text and assisted with data collection. Chad C. Oneway assisted with data collection. Greg Prelewicz assisted with data collection. Brian Steglitz assisted with data collection. Bethany Laursen contributed text to the manuscript. Kristin Rowles contributed text to the manuscript. Shannon Curtis assisted with data collection. Ashley Studholme assisted with data collection. All authors contributed to reviewing and editing the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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