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Authors

Grant, Stanley B
Rippy, Megan A
Birkland, Thomas A
et al.

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Feature

Can Common Pool Resource Theory Catalyze Stakeholder-Driven Solutions to the Freshwater Salinization Syndrome?

Stanley B. Grant,* Megan A. Rippy, Thomas A. Birkland, Todd Schenk, Kristin Rowles, Shalini Misra, Payam Aminpour, Sujay Kaushal, Peter Vikesland, Emily Berglund, Jesus D. Gomez-Velez, Erin R. Hotchkiss, Gabriel Perez, Harry X. Zhang, Kingston Armstrong, Shantanu V. Bhide, Lauren Krauss, Carly Maas, Kent Mendoza, Caitlin Shipman, Yadong Zhang, and Yinman Zhong

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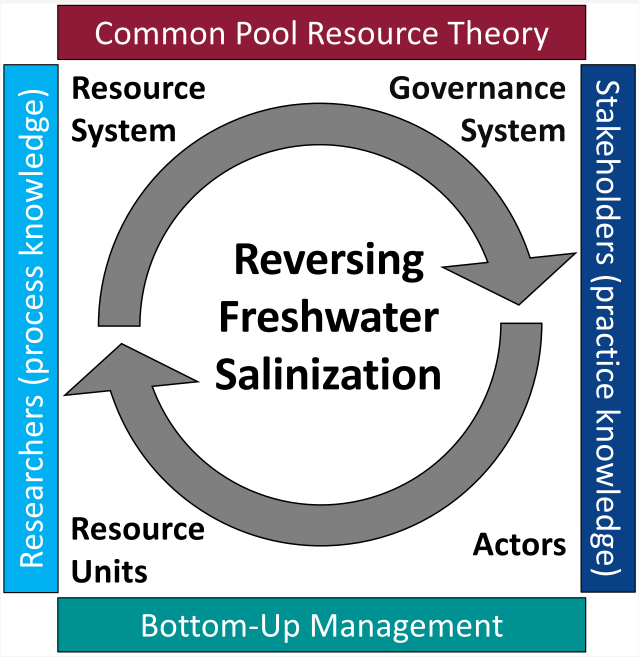
ABSTRACT: Freshwater salinity is rising across many regions of the United States as well as globally, a phenomenon called the freshwater salinization syndrome (FSS). The FSS mobilizes organic carbon, nutrients, heavy metals, and other contaminants sequestered in soils and freshwater sediments, alters the structures and functions of soils, streams, and riparian ecosystems, threatens drinking water supplies, and undermines progress toward many of the United Nations Sustainable Development Goals. There is an urgent need to leverage the current understanding of salinization's causes and consequences—in partnership with engineers, social scientists, policymakers, and other stakeholders—into locally tailored approaches for balancing our nation's salt budget. In this feature, we propose that the FSS can be understood as a common pool resource problem and explore Nobel Laureate Elinor Ostrom's social-ecological systems framework as an approach for identifying the conditions under which local actors may work collectively to manage the FSS in the absence of top-down regulatory controls. We adopt as a case study rising sodium concentrations in the Occoquan Reservoir, a critical water supply for up to one million residents in Northern Virginia (USA), to illustrate emerging impacts, underlying causes, possible solutions, and critical research needs.



KEYWORDS: *Inland Freshwater Salinization, Environmental Regulations, Ion Thresholds, Common Pool Resource Theory, Elinor Ostrom Social-Ecological Systems*

■ INTRODUCTION

> *"The most fruitful of the ancient systems was created at the southeastern end of the Fertile Crescent, the broad valley formed by the Tigris and the Euphrates in what is now Iraq···At its peak of productivity each irrigated region probably supported well over a million people. All these civilizations ultimately collapsed, and for the same reason: the land became so salty that crops could no longer be grown···Although floods, plagues and wars took their toll, in the end the civilizations based on irrigation faded away because of salinization." —Arthur F. Pillsbury*[1]

Communities across the United States and around the world increasingly face the same fundamental challenge that undermined civilizations in the Fertile Crescent thousands of years ago: *achieving salt balance.*[2] A recent U.S. Geological Survey assessment of 422 streams in the United States concluded that inland "freshwaters are being salinized rapidly in all human-dominated land use types".[3] In a recent modeling study, Olson[4] predicted that unless action is taken specific conductance (one measure of salinity) will increase by greater than 50% in more than half of United States streams by 2100.

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At a continental scale, inland freshwater salinization is evidenced by widespread and concomitant increases in ionic strength, base cations, alkalinity, and pH—a pattern that has been termed the freshwater salinization syndrome or FSS.[5]

The FSS is a direct assault on our resource needs and freshwater ecosystems. California's agricultural output, which is 12% of the U.S. total,[6] declined by 7.9% (or $3.7 bn) in 2014 due to salinization.[7] Globally, greater than 40% of the world's food production is impacted by salinization.[8] Rising salinity of drinking water supplies adversely affects the taste of drinking water[9] and accelerates the leaching of heavy metals, such as lead, from water plumbing and water pipes by dezincification and galvanic corrosion.[10] In surface water settings, salts displace contaminants previously sequestered in sediments, mobilizing heavy metals and nutrients into sensitive ecosystems and drinking water supplies and reversing hard-won pollution reductions.[11−15] Salinization of streams, most typically studied as chloride enrichment, is associated with declines in pollution-intolerant benthic invertebrates.[16] We are just beginning to understand how freshwater salinization alters the structure and function of soils, streams, and riparian ecosystems.[17−22] Making matters worse, many natural, agricultural, and urban water systems are characterized by long hydrologic memories,[23,24] which can result in so-called legacy pollution,[25] wherein salt and other contaminants continue to be released to sensitive receiving waters days to decades after all inputs have ceased.[26−28]

The origins of the FSS trace back to many of the critical agricultural and engineering systems that define our modern life.[26,29−31] This includes application of anti-icers and deicers on road networks and parking lots,[13,31−36] wastewater and industrial discharges,[37−39] the weathering of concrete,[5,40−43] agricultural return flows,[44] as well as the accelerated weathering of geologic material from the environmental release of strong acids and the human excavation of rock, which currently exceeds natural denudation processes by an order of magnitude.[45,46]

Except for chloride,[22] current regulations to protect water quality in the United States do not typically address inland freshwater salt pollution.[16] In lieu of, or as a complement to, top-down regulation, in this feature, we focus on bottom-up stakeholder-driven solutions to this environmental grand challenge. Specifically, we propose that inland freshwater salinization can be understood as a common pool resource problem, where the resource is the capacity of inland freshwaters to assimilate salt, for example, by dilution with a renewable source of low salinity freshwater.[47] Common pool resources differ from traditional public and private goods in two ways:[48] (1) The resource is available to all users (i.e., excluding users is difficult or would be unwise). (2) The use of the resource by one user decreases its availability or benefits for others (i.e., the resource is subtractable). Inland freshwater salinization meets both criteria. Practically speaking, it would be difficult to prevent individuals in a watershed from using excessive amounts of deicer on their driveways during winter or pouring salt-rich products down the sink in their homes—practices that add salt to inland freshwaters, where they consume salt assimilative capacity. Furthermore, consumption of salt assimilative capacity by one user leaves it less available for other users in the watershed. The common beneficiaries of freshwater resources therefore need to find ways to control inland freshwater salinization as part of watershed management.

Political scientists and economists have long debated how to best manage common pool resources. Proposed approaches include government interventions and regulations, privatization and the use of market mechanisms for efficient distribution, and self-governance by individuals and entities who have the most to lose if the resource is depleted.[48] For example, Cañedo-Arguelles et al.[49] argue that the ecological impacts of the FSS should be addressed through the imposition of "salinity standards for specific ions and ion mixtures···developed and legally enforced to protect freshwater life and ecosystem services." Others have also argued for expanding existing regulations (which in the United States focus primarily on the impact of chloride on stream ecosystems[22]) to keep freshwater salinity within safe operating limits.[16,50,51]

Top-down regulatory control is often rooted in the logic of the "tragedy of the commons", which supposes that, in the absence of restraints imposed by government or private ownership, individual consumers of a common pool resource will always prioritize personal gain over the collective's well-being, thus inexorably leading to resource depletion.[52] There are certainly examples where this has occurred,[53] but there are also many counterexamples where top-down interventions and privatization accelerated resource destruction.[48] Indeed, political economist Elinor Ostrom won the Nobel Memorial Prize in Economic Sciences in 2009 for her extensive empirical research demonstrating that, contrary to the tragedy of the commons, communities often self-organize to manage the use of a resource in ways that alleviate the threat of resource depletion without the imposition of traditional regulatory measures.[54,55] In the end, the FSS, like many national and international environmental grand challenge problems, is probably best addressed through hybrid bottom-up and top-down approaches that stimulate "dialogue among interested parties, officials, and scientists; complex, redundant, and layered institutions; a mix of institutional types; and designs that facilitate experimentation, learning and change".[56]

In this feature, we suggest that Ostrom's social-ecological systems (SES) framework for common pool resource problems can be used as a diagnostic tool for identifying the context-specific barriers and opportunities for collective (bottom-up) management of the FSS. First, we provide an overview of the FSS as a complex socio-ecological problem, outline its linkages to myriad other socio-ecological problems and sustainable development goals, and describe our study site in northern Virginia, where rising sodium concentration is threatening a critical drinking water supply. We then orient readers to Ostrom's SES framework, map out the social-ecological feedbacks for our study site, and identify the challenges and opportunities for stakeholder-driven management of inland freshwater salinization. We conclude by outlining a series of questions for future research.

■ FSS AS A COMPLEX SOCIO-ENVIRONMENTAL PROBLEM

FSS and UN Sustainable Development Goals. The FSS is intertwined with the functioning of our societies and pursuit of environmental, social, and economic sustainability. This point is illustrated by the many reciprocal relationships that exist between the FSS and the United Nations Sustainable Development Goals (SDGs), aspirational goals adopted by the UN General Assembly to address some of the greatest challenges of our time.[57] The FSS undermines the protection of inland ecosystems (SDG 6)[49] and the protection of drinking water supplies (SDG 15).[10,38] While several SDGs might mitigate the FSS, the pursuit of others could work against efforts to reduce inland freshwater salinization.[58] Improving air quality (SDGs 11.6 and 13) could reduce the FSS by reducing atmospheric deposition of weathering agents such as H_2SO_4, HNO_3, and H_2CO_3, which accelerate the leaching of salts from natural geologic formations, exposed rock, and concrete infrastructure (such as roads, canals, and bridges).[5] On the other hand, the pursuit of affordable and clean energy (SDG 7), responsible consumption and production (SDG 12), and increased food production (SDG 2) could increase salt mass loading to inland freshwaters from industry, mining, oil production, fracking, agriculture, and biofuel production.[44,58−61] Improved water and sanitation (SDG 6) can convey salts from myriad sources (described later) to shallow groundwater in the case of onsite sewage disposal systems[62] and to streams from centralized wastewater treatment facilities.[37−39] Sustainable ("green") stormwater infrastructure (SDG 9.1) funnel deicers into shallow groundwater.[34,63] Road and parking lot deicers and anti-icers are a leading cause of freshwater salinization in colder climates, but limiting their use might conflict with efforts to improve road safety (SDGs 3.6 and 11.2).

Salinization of the Nation's First Large-Scale Indirect Potable Reuse System. An example of the transdisciplinary challenge posed by the FSS is sodium build-up in the Occoquan Reservoir, a drinking water resource for up to one million people in northern Virginia, USA (Figure 1). In the 1960s, nutrients discharged from many small (neighborhood-scale) treatment plants caused frequent algal blooms in the Occoquan Reservoir. This led to the passage in 1971 of the Occoquan Policy (codified in the Virginia Administrative Code at 9 VAC 25-410), which led to the construction of a single "high-performance regional plant, the Upper Occoquan Sewage Authority (UOSA), and the elimination of 11 low-performance treatment plants in favor of the UOSA facility." Because this system was also one of the nation's first large-scale experiments in deliberate indirect potable reuse (i.e., the practice of deliberately adding highly treated wastewater to reservoirs and groundwater basins used for potable supply,[64] as opposed to the much more common practice of defacto reuse, where drinking water supply intakes are impacted by upstream wastewater discharges in an unplanned way[65,66]), the policy also mandated the formation of an Occoquan Watershed Monitoring Committee to oversee the operation of UOSA and to develop a "water quality monitoring program for the Occoquan reservoir and its tributary streams···to ensure that projections are made to determine the effect of additional waste loading from point sources as well as nonpoint sources." The policy goes on to note that "in the future it may be necessary that additional mandatory [non-point source] programs be adopted."

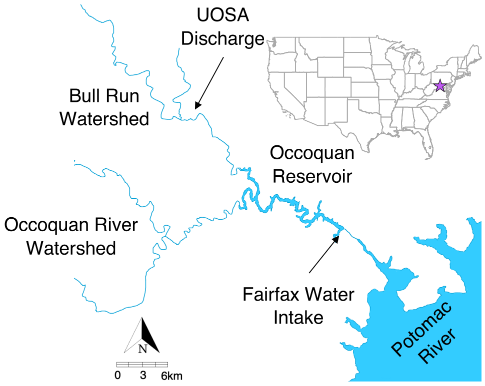
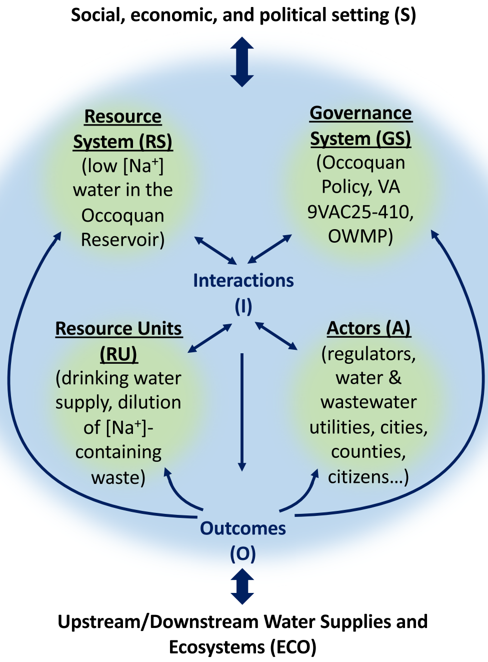


Figure 1. The Occoquan Reservoir is the nation's first large-scale deliberate indirect potable reuse system for surface water augmentation. Inflow to the reservoir includes base flow and storm runoff from the Occoquan River and Bull Run watersheds, along with up to 54 million gallons per day of reclaimed water from the Upper Occoquan Service Authority (UOSA). Water from the Occoquan Reservoir is treated by Fairfax Water, the water wholesaler, and from there passes to various water distributors for up to 1 million drinking water customers in Northern Virginia.

The success of this experiment in water reclamation continues to inspire the construction of similar facilities around the country and world.[67] However, starting around 1995, sodium concentrations in the Occoquan Reservoir began to rise[38] and now regularly exceed the drinking water health advisory for individuals on a severely restricted sodium diet (20 (Na^+) mg/L) and the lower drinking water taste threshold (30 (Na^+) mg/L) issued by the United States Environmental Protection Agency (EPA).[9,68] Concerned that this upward trend might continue, the local water purveyor (Fairfax Water) began exploring planning-level options, including a reverse osmosis treatment upgrade that would likely cost more than $1 billion (or roughly $1000 per customer), not including brine disposal costs, energy and carbon footprint costs, and lost production capacity.[69] Scaled up to the 50+ million people living in the Mid-Atlantic where salinity is rising quickly[3] and projected to continue increasing,[4] the capital costs alone of "desalinating freshwater" in the region could potentially exceed $50 billion. Further, this problem is unlikely to be solved using top-down regulatory approaches (e.g., by setting wasteload and load allocations for point and nonpoint sodium sources in the watershed, respectively, through a total maximum daily load, or TMDL, process) because only a handful of states, not including Virginia, have adopted sodium-specific thresholds, or criteria, for drinking water.[16]

Cross-Sectoral Challenges of Managing the FSS in Urban Settings. Most of the sodium load entering the Occoquan Reservoir can be traced back to three sources—reclaimed water discharged from UOSA and two rapidly urbanizing watersheds that drain into reservoir tributaries (Figure 1). Based on 25 years of water quality measurements, sodium mass loading to the reservoir is primarily from watershed runoff during wet weather and reclaimed water during dry weather.[38] However, even though storm and sanitary sewer systems are separate in this region, wet weather runoff and wastewater treatment systems are inextricably linked, such that factors that contribute salt to the former ultimately contribute salt to the latter as well. In the Occoquan system, water and sodium entering the reservoir from the Bull Run and Occoquan River tributaries (e.g., from the application of rock salt, NaCl, on roads during winter storms) is pumped into a water treatment plant where more sodium is added as part of the water treatment process (for chlorination, pH control, and corrosion control).[70] From there, the water and sodium flow through pressurized drinking water distribution systems to homes, businesses, and industry where additional sodium is added from the flushing of human urine and feces down the toilet, the down-drain disposal of common household products (e.g., from soaps and detergents[71]),



Ten Key Second-Level Variables
(1) RS3: Size of the resource system
(2) RS5: Productivity of the system
(3) RS7: Predictability of system dynamics
(4) RU1: Resource unit measurement
(5) GS6: Collective-choice rules
(6) A1: Number of users
(7) A5: Leadership/entrepreneurship
(8) A6: Norms/social capital
(9) A7: Knowledge of SES/mental models
(10) A8: Importance of resource

Figure 2. (Left) Ostrom's Social-Ecological-Systems (SES) framework for common pool resource management, applied here to sodium $[Na^+]$ management in the Occoquan Reservoir (after Ostrom[74]). Green circles represent first-level subsystems. OWMP, Occoquan Watershed Monitoring Program. (Right) 10 key second-level variables associated with the likelihood that collective management of the resource is feasible (alphanumeric codes from Ostrom[74]). Similar diagrams can be prepared for other ions and ecosystem services.

residential water softeners,[72] and permitted industrial discharges (e.g., from a large microfabrication facility). Sodium in the wastewater then flows through a sewage collection network to one of several regional wastewater treatment plants, including UOSA, where additional sodium is added as part of the treatment process (for chlorination, dechlorination, and odor control).[70] Water and sodium from the UOSA water reclamation facility is discharged to the Bull Run tributary of the Occoquan Reservoir.

Bottom-up management of sodium in this system will therefore entail overcoming significant cross-sectoral challenges. The Occoquan system encompasses at least eight different utilities and government agencies working in very different sectors, including the local drinking water utility (Fairfax Water), the wastewater reclamation facility (UOSA), the state transportation agency (Virginia Department of Transportation, which manages deicer and anti-icer application on state-owned roads), and separate city and county departments in five jurisdictions responsible for winter road maintenance and their municipal separate storm sewer systems, which transfer road salts to tributaries of the Occoquan Reservoir during storms (City of Manassas, City of Manassas Park, Prince William County, Fairfax County, Loudoun County, Fauquier County). While daunting, it is often the case that such diverse entities can cooperatively manage a local common pool resource without the imposition of top-down command-and-control regulation, an arrangement known as "polycentric governance."[54] As Ostrom found in her 1965 doctoral dissertation—a dissertation devoted to understanding how water managers addressed the problem of salt intrusion into groundwater sources[73]—polycentric governance can be particularly effective for managing common pool resources in the water sector.

SOCIAL-ECOLOGICAL SYSTEM (SES) FRAMEWORK

From detailed studies of collective action arrangements in environmental management, Ostrom argued that common pool resource systems can be understood as a SES, "composed of multiple subsystems at multiple levels analogous to organisms composed of organs, organs of tissues, tissues of cells, cells of proteins, etc."[74] The structure of, and feedbacks embedded in, an SES determine the likelihood of "particular policies enhancing sustainability in one type and size of resource system and not in others".[74]

First-Level Variables Applied to the Occoquan System. The SES consists of a set of first-level subsystems—including the Governance System (first-level variable GS), Resource System (RS), Resource Units (RU), and Actors (A)—all of which are contextualized within a social, economic, and political setting (S) and exhibit two-way interactions with each other and related ecosystems (ECO).

To apply the SES framework to sodium build-up in the Occoquan Reservoir, we adopted a case analysis approach,[75] relying on our prior work at this site, facilitated discussions and one-on-one interviews with stakeholders, previously published literature, and an analysis of the history of the Occoquan governance system. The first-level variables can be mapped to the Occoquan system as follows (Figure 2): Governance System: The Occoquan Policy and associated actor networks that collectively formulate and implement environmental policy and policy instruments in the Occoquan system, including the Occoquan Monitoring Program subcommittee. Resource System: Freshwater in the Occoquan Reservoir with low-sodium concentration (e.g., <20 mg/L). Resource Units: The assimilative capacity of the reservoir to accept sodium (e.g., through dilution by renewable freshwater[47] and uptake by ion exchange[50]) and maintain critical ecosystem services,

Table 1. Assessing the Likelihood of Collective Management of Freshwater Salinization in the Occoquan Reservoir through the Lens of SES's 10 Second-Level Variables

Second-level variable	Definition	Positively or negatively associated with collective management	Status in the Occoquan
Resource systems			
RS3	Size of the resource system	Negatively associated	Salt is added by many different entities across multiple jurisdictions which poses challenges for collective management.
RS5	Productivity of the system	Positively associated	The Occoquan Reservoir is highly productive from a water supply perspective, providing drinking water for ~1 M people in northern Virginia. Its productivity may be limited, however, by its limited capacity to accept salt.
RS7	Predictability of system dynamics	Positively associated	Predictability is poor, because of extreme variability (e.g., storm flows), limited monitoring (e.g., deicer application), and the complex and intertwined nature of the various contributing systems. However, understanding of the system is improving.
Resource units			
RU1	Resource unit mobility	Negatively associated	"Due to the costs of observing and managing a system, self-organization is less likely with mobile resource units, such as wildlife or water in an unregulated river, than with stationary units such as trees and plants or water in a lake" (Ostrom,[74] p 421). By this definition, water in the reservoir is immobile, although the addition of salt occurs all along flow paths that lead to the reservoir (see main text).
Governance systems			
GS6	Collective-choice rules	Positively associated	When users can develop their own resource management rules, collective action comes with lower transaction costs and lower costs in regulating the use of the resource. The Occoquan Policy provides a potential framework for the development and implementation of collective choice rules.
Actors			
A1	Number relevant actors	Negatively associated	With approximately 1 M drinking water customers, and at least eight different transportation authorities, utilities, and city and county governments, there is a relatively high cost of "getting users together and agreeing on changes," but large numbers of users can share the tasks and costs of monitoring (Ostrom,[74] p 421).
AU5	Leadership/entrepreneurship	Positively associated	There are entrepreneurial leaders with established records in their communities, including leadership around the development of innovative frameworks for managing salts from winter maintenance activities.[81]
A6	Norms (trust reciprocity) and social capital	Positively associated	The Occoquan Policy serves as a formal institution (i.e., a set of norms and rules) for managing water quality in the reservoir. It is based on collaboration and consensus building, thereby promoting the collective management of this resource (see main text).
A7	Knowledge of SES/mental models	Positively associated	Knowledge of the SES is currently being evaluated and may improve over time with selective interventions and through our current research project.
A8	Importance of resource	Positively associated	The reservoir is of high local value for drinking water, wastewater assimilation, recreation, and aquatic wildlife habitat.

including the provisioning of drinking water and critical habitat. Actors: Stakeholders in the watershed, including regulators, drinking water utilities, wastewater and water reclamation utilities, cities, counties, transportation departments, manufacturing plants, private citizens, and so on.

Second-Level Variables Applied to the Occoquan System. Under each first-level variable is a set of second-level variables that can influence collective management to varying degrees depending on context.[76] According to Ostrom, 10 of these second-level variables, in particular, are often found to be positively or negatively associated with the likelihood that stakeholders or government agencies will self-organize to collectively manage common pool resource problems.[74,77] In this section, we present a preliminary assessment of the Occoquan system through the lens of these 10 second-level variables, which are indicated by their Ostrom-assigned alphanumeric codes (right side of Figure 2 and first column of Table 1). For example, the code "RS3" denotes the size of the resource system, which is part of the subsystem "Resource System."

The assessments in Table 1 reveal both opportunities and challenges for the self-organization of actors around the collective (polycentric) management of sodium build-up in the Occoquan Reservoir. Here, the term "actor" includes users of the resource (i.e., users of the reservoir's salt assimilative capacity, such as UOSA), as well as participants in the governance system that are not direct users of the system, such as regulators.[77] Many actors are organized around the Occoquan Policy and engaged in the governance of UOSA. The UOSA board of directors consists of representatives from the local governments served by this regional water reclamation facility. Furthermore, the Occoquan Watershed Monitoring Program brings together regulators, practitioners, and water quality experts to ensure that the quality of the water drawn from the Occoquan Reservoir meets regulatory and performance standards. The existence of these governance structures means that actors are regularly communicating with each other, engaging in what Ostrom calls "cheap talk".[54] Cheap talk—frequent communication with minimal transaction costs—is a key factor that distinguishes effective polycentric common pool resource management from a model of human behavior in the putative tragedy of the commons, which assumes there is no communication between users of a resource, and the only signals received are about individual utility maximization and the overall performance of the system.[54]

CHEAP TALK AND STAKEHOLDER MENTAL MODELS OF THE SES

To evaluate the extent to which "cheap talk" is already creating a shared understanding of the Occoquan system, and with the goal of specifically evaluating the extent to which stakeholders have a common mental model of this SES (second-level variable A7; Table 1), our research team has conducting semistructured interviews with 41 local stakeholders (including representatives from city and county governments; state, federal, and interstate agencies; research foundations; consulting firms; NGOs; and industry) with the goal of generating "fuzzy cognitive maps" or FCMs. FCMs are graphical representations of stakeholder mental models of the SES that include key system components, the positive or negative relationships between these components, and the degree of influence that one component can have on another, defined with qualitative weightings (e.g., high, medium, or low influence).[78−80] In our application, the FCMs depict stakeholder understanding of potential sources of salt, social and ecological consequences of salinization, and possible actions that could be taken to address the problem. While FCM collection is still underway, early results suggest that stakeholder mental models of the Occoquan SES are structurally diverse, ranging from linear maps that focus on a single cause of salinization and its distal drivers (e.g., salts added by winter maintenance activities in the public sector fueled by population/economic development and increasing imperviousness) to complex networks of interrelated causes and salt sources (e.g., salts added by winter maintenance activities, industrial effluents, use of in-home products, and chemicals used in drinking water and wastewater treatment), all fueled by population and economic development.

This structural variability—including the concepts stakeholders choose to include, as well as the degree to which the concepts are linked together in complex networks—indicates that there is still substantial opportunity for shared learning around this SES. There is also evidence that "cheap talk" associated with the development of a Salt Management Strategy Toolkit for Northern Virginia (SaMS)[81] has increased consensus around the importance of winter maintenance activities as a driver of freshwater salinization in the region.

The FCMs are also revealing complex feedbacks like those described in the socio-hydrology literature.[82,83] In one example, salts added during drinking water treatment increase drinking water salinity which, in turn, decrease customer acceptance. This balancing (or negative) feedback loop acts to keep salts added by drinking water treatment in check. In another example, the ability to use the Occoquan Reservoir for indirect potable reuse incentivizes reduced salt use in wastewater treatment. This reduces watershed salinization, which promotes additional indirect potable reuse, in effect creating a reinforcing (or positive) feedback loop that links increasing indirect potable reuse practices to long-term reductions in reservoir salinization through the incentives they provide wastewater utilities to manage salt additions wisely. We hypothesize that continuing "cheap talk" around these and other features of the FCMs, facilitated in the context of our research project using the joint fact-finding methodologies described below, can facilitate the emergence of new norms and rules, or institutions, for managing salt inputs to this system.

BIG UNKNOWNS AND CRITICAL RESEARCH NEEDS

This first application of common pool resource theory to the FSS highlights several big unknowns and critical research needs going forward.

First, as part of our National Science Foundation Growing Convergence Research (NSF GCR) project, stakeholders and research team members (including engineers, policy scholars, geochemists, and biologists) are engaging in joint fact finding (JFF)[84] and other knowledge coproduction methodologies (Ostrom's SES, FCMs) to codefine critical research needs for the Occoquan system, cocollect and cointerpret data, and ultimately coidentify actions that could be taken to limit, and ideally reverse, rising sodium concentrations in the reservoir. These knowledge coproduction processes[85,86] are enhancing the predictability of system dynamics (RS7) and contributing to stakeholders' collective knowledge of it (A7). Over time, what influence will these and other forums for repeated interactions ("cheap talk") and shared learning (JFF) have on the stakeholders' mental models of salinization of the Occoquan Reservoir (e.g., as represented by convergence of their FCMs)? Will convergence of stakeholder understanding of the FSS catalyze the emergence of new rules and norms (e.g., agreed upon ion-specific thresholds, see below) for the polycentric management of sodium loads?

Second, can tools from network and information sciences[87,88] be brought to bear on the evaluation of stakeholder FCMs, for example, describing key features of the SES using model aggregation to capture the collective wisdom of diverse stakeholders (e.g., wisdom-of-the-crowd approaches[79])? How might aggregated models be used to convey, for example, through simulations, complex interactions that help stakeholders understand trade-offs,[89] such as when an action fosters one valued outcome but has an adverse effect on another? For that matter, what are the best approaches for identifying and tracking areas of agreement and disagreement across mental models of the SES at different levels (individual level, subgroups of peers, diverse stakeholder collective), and what do differences in the convergence trajectories across these groups tell us about how knowledge of the SES (second-level variable A7, Table 1) propagates and evolves? This last question speaks to the importance of considering Ostrom's second-level variables as dynamic rather than static and a shift toward an SES framework for freshwater salinization that is more than just descriptive.[90]

Third, how might well-intentioned efforts to reverse the FSS fail, or even backfire and make things worse, due to hidden interactions and feedbacks embedded in the SES?[82,83] Many such interactions and feedbacks have already been discussed in the context of two-way linkages between freshwater salinization and the UN SDGs, interactions between subsystems in the SES framework (Figure 2), the highly intertwined nature of urban water systems and other critical engineered infrastructure that contributes to salinization, and positive and negative feedback loops within the Occoquan SES that may act to buffer salt concentrations in the system. As these interactions and feedbacks are elucidated and explored, to what extent will members of the governance system understand, appreciate, and act upon this knowledge?

Fourth, can the knowledge coproduction frameworks, approaches, and tools being trialed in the Occoquan system (i.e., Ostrom's SES, JFF, and FCMs) be scaled-up to address the FSS in other regions and contexts? For example, given the site-specific nature of the FSS (including potential salt sources and their human and ecosystem impacts[91]) and the limited and patchy nature of enforceable ion-specific thresholds across the United States and globally,[16] could these transdisciplinary methods be applied more generally to foster local consensus around ion-specific thresholds, in support of polycentric governance of the FSS?

Finally, which of the SES's second-level variables are critical to solving the FSS, and to what extent is the answer context-specific? From our initial work, several second-level variables appear to favor the potential for collective management, while other variables present potential challenges. The Occoquan system is particularly strong in terms of norms and social capital (A6), through the Occoquan Policy and related institutions. Our NSF GCR project is building knowledge to improve system predictability (RS7), seeking opportunities for collective-choice rules (GS6), and evaluating whether and how convergence of SES knowledge (A7) can support collective management. Indeed, our project is animated by the idea that collective (bottom-up) management of the FSS can be catalyzed through a deep collaboration between engineers, natural scientists, social scientists, decision-makers, and other stakeholders, in effect leveraging scientific and engineering insights about the causes and consequences of the FSS into locally tailored solutions to this environmental grand challenge.

■ AUTHOR INFORMATION

Corresponding Author

Stanley B. Grant − *Occoquan Watershed Monitoring Laboratory, The Charles E. Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech, Manassas, Virginia 20110, United States; Center for Coastal Studies, Virginia Tech, Blacksburg, Virginia 24061, United States;* orcid.org/0000-0001-6221-7211; Email: stanleyg@vt.edu

Authors

Megan A. Rippy − *Occoquan Watershed Monitoring Laboratory, The Charles E. Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech, Manassas, Virginia 20110, United States; Center for Coastal Studies, Virginia Tech, Blacksburg, Virginia 24061, United States*

Thomas A. Birkland − *School of Public and International Affairs, North Carolina State University, Raleigh, North Carolina 27695-8102, United States;* orcid.org/0000-0003-3073-8471

Todd Schenk − *School of Public and International Affairs, Virginia Tech, Blacksburg, Virginia 24060, United States*

Kristin Rowles − *Policy Works LLC, Baltimore, Maryland 21211, United States*

Shalini Misra − *School of Public and International Affairs, Virginia Tech, Arlington, Virginia 22203, United States*

Payam Aminpour − *Department of Environmental Health and Engineering, Johns Hopkins University, Baltimore, Maryland 21211, United States*

Sujay Kaushal − *Department of Geology and Earth System Science Interdisciplinary Center, University of Maryland, College Park, Maryland 20742, United States*

Peter Vikesland − *The Charles E. Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, Virginia 24061, United States;* orcid.org/0000-0003-2654-5132

Emily Berglund − *Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, North Carolina 27606, United States*

Jesus D. Gomez-Velez − *Department of Civil and Environmental Engineering, Vanderbilt University, Nashville, Tennessee 37235-1831, United States; Climate Change Science Institute & Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, United States*

Erin R. Hotchkiss − *Department of Biological Sciences, Virginia Tech, Blacksburg, Virginia 24061, United States*

Gabriel Perez − *Department of Civil and Environmental Engineering, Vanderbilt University, Nashville, Tennessee 37235-1831, United States*

Harry X. Zhang − *The Water Research Foundation, Alexandria, Virginia 22314, United States*

Kingston Armstrong − *Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, North Carolina 27606, United States*
Shantanu V. Bhide − *Occoquan Watershed Monitoring Laboratory, The Charles E. Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech, Manassas, Virginia 20110, United States;* orcid.org/0000-0002-5248-0646
Lauren Krauss − *Occoquan Watershed Monitoring Laboratory, The Charles E. Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech, Manassas, Virginia 20110, United States*
Carly Maas − *Department of Geology and Earth System Science Interdisciplinary Center, University of Maryland, College Park, Maryland 20742, United States*
Kent Mendoza − *The Charles E. Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, Virginia 24061, United States*
Caitlin Shipman − *Occoquan Watershed Monitoring Laboratory, The Charles E. Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech, Manassas, Virginia 20110, United States*
Yadong Zhang − *Department of Civil and Environmental Engineering, Vanderbilt University, Nashville, Tennessee 37235-1831, United States*
Yinman Zhong − *School of Public and International Affairs, North Carolina State University, Raleigh, North Carolina 27695-8102, United States*

Complete contact information is available at:
https://pubs.acs.org/10.1021/acs.est.2c01555

Notes

The authors declare no competing financial interest.

Biography

Stanley Grant is a Professor of Civil and Environmental Engineering at Virginia Tech and Director of Occoquan Watershed Monitoring Laboratory in Northern Virginia. Stan's water quality research relies on field experiments, modeling studies, and stakeholder engagement. He has been the Principal Investigator of several interdisciplinary and transdisciplinary center-scale research grants, including the U.S. National Science Foundation Growing Convergence Research project described in this paper.

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