Rippy, M. A., B. H. Roston, E. Z. Berglund, P. Aminpour, L. Krauss, S. V. Bhide, T. Schenk, K. Rowles, S. Misra, T. A. Birkland, S. S. Kaushal, and S. B. Grant. 2024. Characterizing the social-ecological system for inland freshwater salinization using fuzzy cognitive maps: implications for collective management. Ecology and Society 29(4):47. https://doi.org/10.5751/ES-15536-290447

Research

Characterizing the social-ecological system for inland freshwater salinization using fuzzy cognitive maps: implications for collective management

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ABSTRACT. Current regulatory tools are not well suited to address freshwater salinization in urban areas, and the conditions under which bottom-up management is likely to emerge remain unclear. We hypothesize that Elinor Ostrom's social-ecological systems (SESs) framework can be used to explore how current understanding of salinization might foster or impede its collective management. We focus on the Occoquan Reservoir, a critical urban water supply in Northern Virginia, USA, and use fuzzy cognitive maps (FCMs) to characterize stakeholder understanding of the SES that underpins salinization in the region. Hierarchical clustering of FCMs reveals four stakeholder groups with distinct views on the causes and consequences of salinization, and actions that could be taken to mitigate salinization, including technological, policy, and governance interventions and innovations. Similarities and differences across these four groups, and their degree of concordance with measured or modeled SES components, point to actions that could be taken to catalyze collective management of salinization in the region.

Key Words: *collective management; common pool resource; fuzzy cognitive mapping; inland freshwater salinization; social-ecological system; understanding the SES*

INTRODUCTION

Many of the world's streams, rivers, lakes, and reservoirs are becoming saltier, a process known as the freshwater salinization syndrome (FSS; Kaushal et al. 2019, 2021). The FSS poses a direct threat to critical freshwater ecosystems (Findlay and Kelly 2011, Schuler et al. 2019, Velasco et al. 2019) agricultural productivity (Schwabe et al. 2006, Welle and Mauter 2017), and drinking water supplies (Corsi et al. 2010, Bhide et al. 2021), and undermines many of the United Nations' Sustainable Development Goals (Flörke et al. 2019). Origins of the FSS include the application of deicers and anti-icers to roads and parking lots in northern climates, salt-laden discharges from sewage treatment plants, mining and energy extraction operations, and agricultural return flows, to name a few (Wilkinson 2005, Steele and Aitkenhead-Peterson 2011, Welle and Mauter 2017, Schwabe et al. 2020, Bhide et al. 2021, Grant et al. 2022, Hintz et al. 2022, Kaushal et al. 2023*a*).

In many countries, existing water quality regulations are not well suited to manage the FSS, in part because of the ion-, site-, and ecosystem-specific nature of the problem (Cañedo-Argüelles et al. 2013, Schuler et al. 2019, Grant et al. 2022). Few federal regulations presently exist in the United States for individual salt ions (Schuler et al. 2019). Those that do exist include acute and chronic limits for chloride intended to protect aquatic freshwater species, as well as secondary (nonmandatory) guidelines for sulfate, fluoride, and chloride in drinking water (EPA 1988, Schuler et al. 2019, State of Virginia 2019). Every five years, the U.S. Environmental Protection Agency (EPA) publishes a candidate list of unregulated contaminants that may ultimately warrant regulation under the *Safe Drinking Water Act.* Salt ions such as sodium and sulfate have made the list in prior years (e.g., in 1998) but, at the time, were not determined to present a meaningful opportunity to mitigate health risk and were therefore not regulated (EPA 2003*a*). This prior determination may reduce the likelihood of federal regulation in future years, even though salinization has continued to worsen (Kaushal et al. 2019, 2021, 2023*a,b,* Olson 2019, Bhide et al. 2021), and concentrations of specific salt ions that were previously considered low (e.g., 29–60 mg/L of sodium) are increasingly linked to adverse health consequences such as preeclampsia (Thompson et al. 2022).

Given the present challenges associated with regulation, we focus here on locally tailored, stakeholder-driven approaches for addressing the FSS. In urban water systems, stakeholder-driven, collective management represents a radical departure from current strategies for addressing the FSS, which are often source specific and siloed (Kaushal et al. 2018, Bhide et al. 2021), a consequence of the tendency to manage key water subsystems separately (e.g., stormwater, drinking water, wastewater, surface water, and groundwater; Rahaman and Varis 2005). In recent years, urban water practitioners have become increasingly open to integrated management approaches as part of an emerging "One Water" paradigm (Paul et al. 2022). Whether (and how) this openness will translate into new governance arrangements, however, remains unclear.

We argue that Elinor Ostrom's social-ecological system (SES) framework (Ostrom 2009) provides a roadmap for diagnosing (and perhaps fostering) the conditions under which collective management of the FSS is likely to emerge. Ostrom's SES contains 10 second-level variables that have previously been shown (in field studies and meta-analyses) to significantly influence the

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emergence of collective management arrangements (Ostrom 2009, Freeman et al. 2020, Shalsi et al. 2022, Villamayor-Tomas et al. 2022). Work by Grant et al. (2022) calls attention to three of these variables as potential barriers to stakeholder-driven management of the FSS: collective-choice rules, system predictability, and understanding the SES. Here, we focus on one of those variables, understanding the SES, and the ability of novel approaches such as fuzzy cognitive maps (FCMs) both to characterize and to enrich systems knowledge, reducing barriers to collective management.

FCMs are mental models of how a system operates based on its core components (system variables) and the causal links between them (Özesmi and Özesmi 2003). They are often used in the context of participatory modeling as part of a learning process that engages the implicit and explicit knowledge of stakeholders to create formalized and shared representations of reality (Olofsson et al. 2023). This usage makes FCMs well suited for deepening what Emerson et al. (2012) call the "collaborative dynamics" of collaborative governance regimes, which are inclusive of collective management arrangements. Collaborative dynamics involve three interacting components: principled engagement, shared motivation, and capacity for joint action. FCMs are particularly relevant to principled engagement because they can facilitate agreement on the concepts and terminology used to describe problems and lead to the identification of shared interests and objectives (Özesmi and Özesmi 2003, Olofsson et al. 2023). These capabilities complement those of existing deliberative or dialogic approaches for facilitating principled engagement (e.g., soft systems methodology, joint fact-finding; Karl et al. 2007, Checkland and Poulter 2020), particularly with respect to positional bargaining, whereby FCMs help shift stakeholder dialogue from fixed, opposing stances ("my problem definition vs. yours") to the network of relationships that bridge them ("how our views overlap and interact"; Voinov and Bousquet 2010).

FCMs also show promise as an approach for countering cognitive biases and the limitations of bounded rationality, with some studies suggesting that individual stakeholder FCMs can be aggregated to generate a collective model that captures "the wisdom of the crowd" and is therefore more representative of the real-world SES (Aminpour et al. 2020, 2021, Knox et al. 2023). If true, this property could make collective FCMs a valuable tool for shared learning, particularly in systems in which data are limited or problems are viewed in context with social, cultural, or political elements that can be captured by FCMs but are difficult to quantify explicitly, limiting their representation in traditional model frameworks (Özesmi and Özesmi 2003).

Here, we explore the capacity of FCMs to characterize stakeholder understanding of the SES for freshwater salinization, focusing on (1) their ability to reveal barriers and opportunities for stakeholder-driven, bottom-up management of the FSS (capabilities relevant to principled engagement), and (2) their ability to capture physically meaningful information about the SES when aggregated to represent collective perspectives (capabilities relevant to establishing mutual trust and shared learning). We find that perceptions about individual salt sources, their societal and environmental impacts, and how they might be managed, vary, revealing areas of agreement for which bottom-up management is likely (winter salt sources), as well as divergent views (sewershed salt sources, governance approaches) that could represent barriers to collective action or be leveraged as opportunities for shared learning. Although aggregating FCMs does appear to improve their capacity to capture average biophysical conditions, the range of those conditions are better represented by individual or small-group FCMs. This result suggests that evaluating FCMs at different levels of aggregation (individual through collective) adds value, providing an opportunity for perspective taking ("What conditions do our different perspectives capture?") and learning. While our emphasis is on the FSS, the process we describe for upscaling individual knowledge to systems-level understanding of an SES is not salinization-specific and could potentially inform management approaches for many emerging challenges.

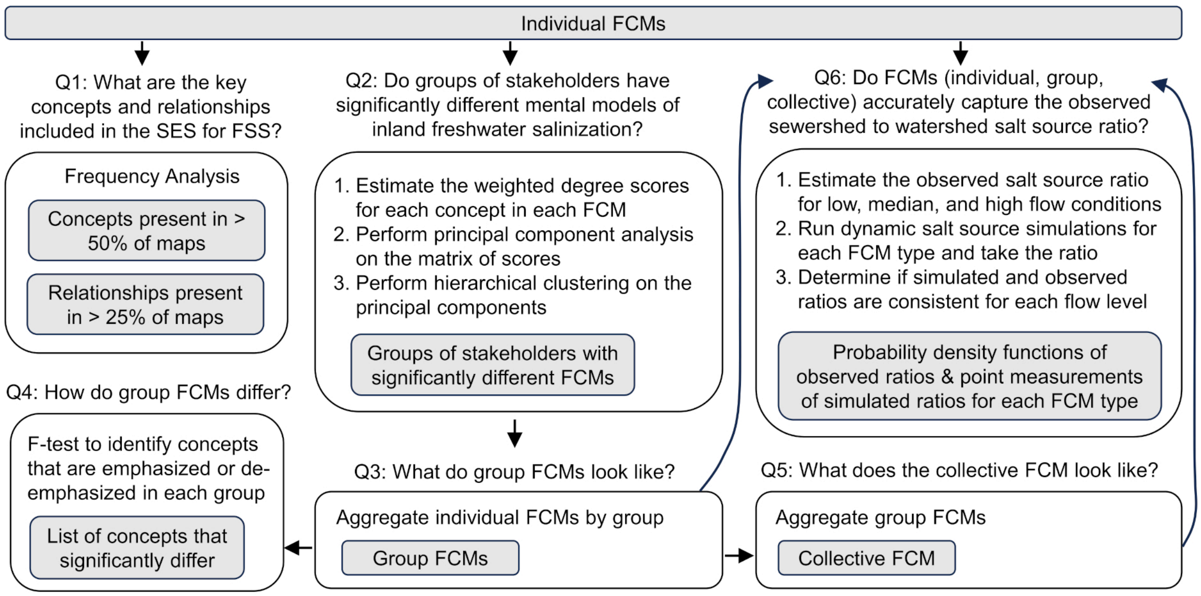
Field site

The Occoquan reservoir is a drinking water resource for up to one million people in northern Virginia, located at the southern end of the Boston-Washington megaregion, one of the world's largest (Adler et al. 2020). The reservoir was the nation's first large-scale experiment in indirect potable reuse, defined as the practice of deliberately introducing highly treated wastewater to surface water or groundwater for potable supply (Grant et al. 2022). Approximately 15% (4.6×10^7 m³/yr) of the reservoir's average annual inflow is highly treated wastewater from the Upper Occoquan Service Authority (UOSA), and the remaining 85% (7.1×10^8 m³/yr) is baseflow and wet weather runoff from two local streams, Bull Run and the Occoquan River, and ungaged watershed flow (Bhide et al. 2021, Grant et al. 2022).

The primary governance system for managing water quality in the reservoir includes both federal (i.e., *Clean Water Act*) and state-specific legislation (i.e., the Occoquan Policy), and the associated network of actors that formulate and implement environmental policy and planning in the Occoquan system. The Occoquan Policy, which is codified in the Virginia Administrative Code at 9 VAC 25-410, mandated the construction of the UOSA wastewater treatment plant for two purposes: (1) to improve drinking-water security in the region by providing a high-quality, drought-proof source of water; and (2) to reduce reservoir eutrophication, which, at the time, was attributed to discharges from 11 low-performance treatment plants to the Occoquan reservoir (Bhide et al. 2021, Grant et al. 2022). The Policy also mandated the formation of the Occoquan Watershed Monitoring Program to oversee UOSA's discharge and monitor reservoir water quality, which has resulted in near continuous monitoring of the system for more than 25 years.

These long-term monitoring data reveal that salinity (e.g., as measured by specific conductance) and concentrations of several salt ions in the reservoir have been increasing over time. The concentration of sodium ions, in particular, occasionally exceeds U.S. EPA guidance on taste and health thresholds for drinking water (EPA 2003*b,* Bhide et al. 2021). The primary source of sodium ions to the reservoir depends on weather conditions (Bhide et al. 2021); namely, UOSA's discharges contribute 60–80% of sodium mass during dry weather, and watershed discharges, particularly Bull Run, contribute 40–60% of sodium mass during wet weather. On average, the total daily mass load of sodium to the reservoir is 42,000 kg/day.

Fig. 1. Flow chart of statistical analyses performed on individual fuzzy cognitive maps (FCMs). FSS = freshwater salinization syndrome, SES = social-ecological system.



METHODS

Fuzzy cognitive map development process

Beginning in summer 2021, 35 stakeholders from in and around the Occoquan system, including water and wastewater utilities (8 total), state and federal governments (8), local cities and counties (6), interstate agencies (5), private corporations, developers, consulting firms or research agencies (5), and environmental nongovernmental organizations (3), participated in a cognitive mapping exercise to construct personalized mental models of freshwater salinization in the Occoquan Reservoir and its tributary streams. All participants were part of the Executive Committee on the Occoquan System (ECOS), which meets quarterly and was formed as part of a U.S. National Science Foundation-funded Growing Convergence Research project geared toward catalyzing stakeholder-driven solutions to freshwater salinization.

Stakeholder mental models were generated via an iterative process (Supplemental Fig. 1 in Appendix 1) that began with co-production of a concept list featuring causes of salinization, consequences of salinization, and actions that might be taken to mitigate salinization. The list was developed using joint fact-finding approaches (Karl et al. 2007), starting with a questionnaire eliciting salt-specific management goals, and culminating in small-group discussions during the first ECOS workshop, where salinization concepts pertaining to these goals were developed and refined.

Following concept list development, one-on-one interviews were conducted to generate individual FCMs of the SES for freshwater salinization using Mental Modeler software (Gray et al. 2013). Each stakeholder's task was to identify the seven most important causes of salinization, consequences of salinization, and actions that could be taken to mitigate salinization (newly created concepts or concepts drawn from the co-developed list) and establish causal connections between them based on their own understanding of the SES (Aminpour et al. 2020, 2021). All stakeholders were required to include salinization of the Occoquan watershed in their models as the central, organizing concept. Once each FCM was complete, it was validated by conducting dynamic simulations whereby all possible mitigating actions were sequentially perturbed so that their impact on all causally-associated concepts could be viewed. Models were revised in real time to meet stakeholder specifications whenever dynamic simulations resulted in outputs that were perceived to be nonsensical.

Following initial FCM collection, de-identified model results were presented at a second ECOS workshop, allowing stakeholders to comment on model concepts and structure and discuss potential modifications. This discussion initiated a process to streamline model concepts (i.e., concept consolidation and final concept list [Supplemental Figs. 2–4 and Supplemental Tables 1–3, respectively, in Appendix 1]). Following the consolidation process, each stakeholder FCM was recast with updated concepts, and a second round of FCM interviews was conducted to review updated models and revise them as needed. These revised FCMs are our best realization of how stakeholders presently understand freshwater salinization in the Occoquan (see Supplemental Fig. 5 in Appendix 1 for individual FCMs) and served as the basis for all analyses conducted here. Next, we describe how individual FCMs were analyzed (see also Fig. 1).

Statistical characterization of similarities and differences

To identify similarities across stakeholder FCMs (concepts and relationships), we first quantified the fraction of FCMs in which each concept was present. Concepts that were present in > 50% of FCMs were retained as core concepts. Once these concepts were identified, the adjacency matrix of each FCM was used to identify common relationships among them (i.e., relationships present in at least 25% of FCMs) that reflect consistencies in how the SES for freshwater salinization is perceived by stakeholders in the Occoquan.

Concept centrality (specifically, weighted degree centrality; Newman 2004) was used to characterize differences across stakeholder FCMs. The centrality of a concept is considered indicative of its contribution in a mental model (i.e., its importance for system dynamics) because it reflects the number of connections between that concept and other concepts, as well as the strength of those relationships (Özesmi and Özesmi 2004, Aminpour et al. 2020). Weighted degree centrality was calculated from the adjacency matrix of each FCM. Concepts that were not included in a given stakeholder's model but were present in others were assigned a weighted degree centrality of zero. This process was repeated for all stakeholders, returning a complete set of weighted degree centrality values for each concept and individual. These values were standardized (subtracting the mean and dividing by the standard deviation) prior to performing principal component analysis (PCA) to identify dominant patterns in the perceived importance of salinization concepts across stakeholders (R package FactoMineR; Lê et al. 2008, Vasslides and Jensen 2016). Standardization keeps the analysis focused on the intrinsic structure of the data (patterns in centrality) and mitigates the influence of differences in FCM size (magnitude of centrality; Davis 2002). Only principal components (PCs) that captured significantly more variance than expected due to chance (resampling-based stopping rule, 95% confidence level) were retained (Peres-Neto et al. 2005, Rippy et al. 2017). Hierarchical clustering of these components was used to identify groups of stakeholders with significantly different perspectives about freshwater salinization. We elected to characterize divergent stakeholder groups in this way because it is entirely inductive (i.e., it is independent of our preconceived notions about what might make stakeholder perceptions different). Clustering was performed using Ward's criterion, followed by k-means consolidation (R package HCPC; Lê et al. 2008). Concepts that were significantly over- or under-represented in a particular stakeholder group were identified using an F-test ($P < 0.01$ level; Husson et al. 2010).

Fuzzy cognitive map aggregation (group and collective models)

Individual FCMs belonging to each stakeholder group identified above (i.e., each significant cluster) were aggregated to create mental models that best characterize the SES for freshwater salinization perceived by these groups. Aggregation was performed as in Aminpour et al. (2020) by taking the mean of the weighted adjacency matrix for all FCMs within each group, omitting zero values (i.e., only relationships for which weights were provided were included in each average).

A collective model representing all stakeholders' insights was also created. This model used approaches developed to leverage wisdom of the crowd and reduce biases associated with shared experiences and knowledge (Aminpour et al. 2020, 2021). Addressing these biases is important because the stakeholder pool we interviewed is not balanced (i.e., we have different numbers of individuals across disciplines and practices, which can give certain perspectives more power than others if not corrected for; Lorenz et al. 2011, Navajas et al. 2018). To address this bias, Aminpour et al.'s (2020) two-step aggregation approach was used, whereby the aggregate models for each stakeholder group (i.e., representing significantly different perspectives; see above) were themselves aggregated by taking the median of their respective adjacency matrices, giving each perspective equal weight in the final collective model.

Dynamic simulation (perceived impact of various salt sources)

The dynamic behavior of FCMs was assessed by changing the activation value of one or more model concepts (i.e., salt sources) and quantifying the impact (change relative to baseline) on the central concept "Salinization of the Occoquan" (Özesmi and Özesmi 2004, Aminpour et al. 2020). Simply put, when different causes of salinization are activated in a FCM (i.e., their activation value is set to 1), it triggers a cascade through all causally connected concepts in the network, including the central concept, "Salinization of the Occoquan Watershed". This procedure allows us to evaluate the relative impact that increasing different salt sources is perceived to have on reservoir salinization for any mental model of the SES. Simulations were performed to evaluate bulk sewershed salt sources (in-home products, industry, water and wastewater treatment), bulk watershed salt sources (winter maintenance chemicals, local geology, agriculture, infrastructure corrosion), and the various subsources that compose them. Simulations were conducted in R using the package fcm (Dikopopoulou and Papageorgiou 2017). Mathematical details are provided in Appendix 1 (Supplemental Methods).

Comparison with biophysical measurements

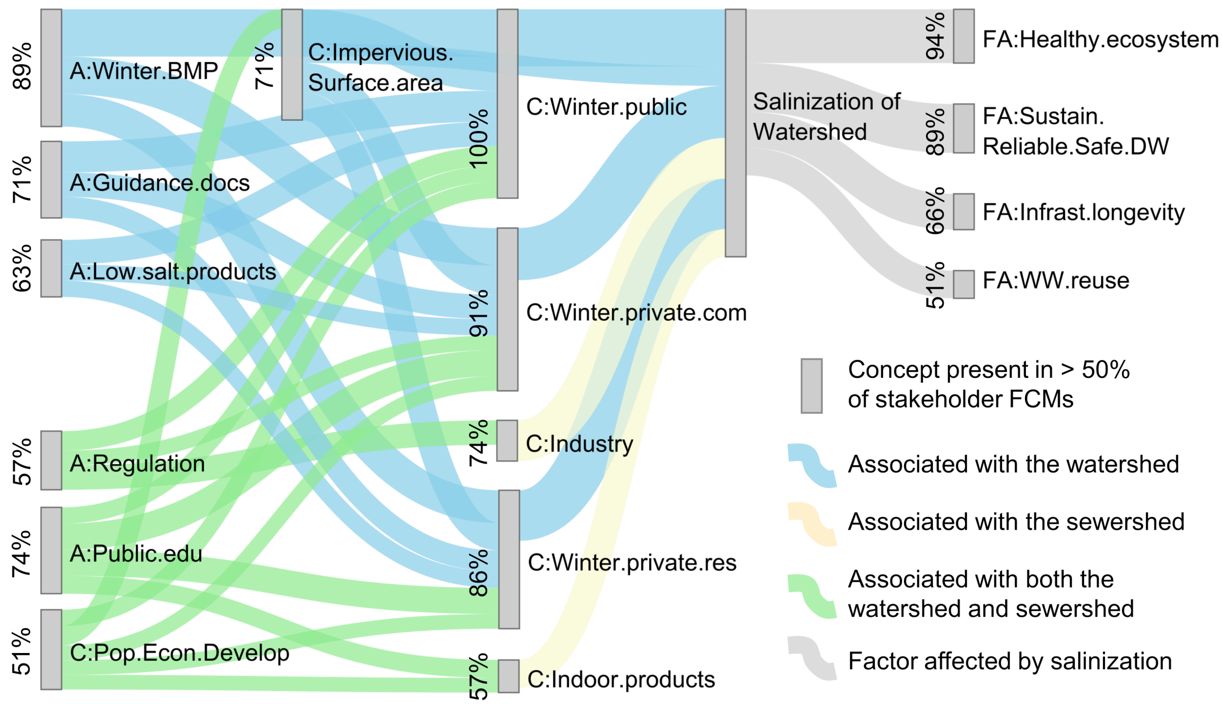
Perceived sewershed-to-watershed salt ratios from dynamic FCM simulations (see above) were compared to biophysical estimates of sodium loading from these two sources to the Occoquan Reservoir. Details of these estimates are provided in Bhide et al. (2021). Briefly, daily time series of sodium mass load were estimated for UOSA (the sewershed) and Bull Run and the Occoquan River (the watershed) using multiple linear regression. Best-fit models (31–87% variance explained) were used to generate an eight-year synthetic daily time series of sodium concentrations at each location that was combined with measured daily flow using the U.S. Geological Survey package Loadflex, generating an eight-year daily time series of sodium load from each source. A bivariate copula was used to join marginal probability distributions of sodium mass load from each source to cumulative flow across all sources to illustrate how the contribution of different sodium sources to overall sodium mass loading varies with local weather conditions (low flow: 2.55 m^3/s, median flow: 6.91 m^3/s, high flow: 31.0 m^3/s). Probability density functions for the sewershed to watershed sodium ratio, conditioned on flow, were developed using this relationship.

RESULTS

Seventeen key knowledge concepts

Seventeen concepts were common across stakeholder FCMs (i.e., present in > 50% of models; Fig. 2). Frequently mentioned causes of salinization included population and economic development in the watershed (51% of models); watershed imperviousness (71% of models); the application of deicers and anti-icers to roads and parking lots during winter (henceforth referred to as "winter maintenance activities") by public agencies (100% of models), private companies (91% of models), and residential communities

Fig. 2. Sankey diagram illustrating common concepts and associations in stakeholder mental models of salinization of the Occoquan Reservoir and its tributaries (grey boxes). The percentage of stakeholder fuzzy cognitive maps (FCMs) that include each concept is reported to the left of the grey boxes; only concepts appearing in > 50% of stakeholder FCMs are shown. Box height reflects the cumulative number of associations between a concept and other concepts to which it is connected, across all stakeholder FCMs. Colored connections indicate whether a concept is primarily associated with salt from the watershed (blue), sewershed (yellow), or both (green), or is a perceived consequence of freshwater salinization (grey). The width of each connection reflects the number of stakeholders that included it across all FCMs; only connections appearing in > 25% of stakeholder FCMs are shown. A = mitigating action, C = cause of salinization, FA = factor affected by salinization, BMP = best management practice, res = residential, com = commercial, DW = drinking water, WW = wastewater, Pop.Econ.Develop = population and economic development, docs = documents.



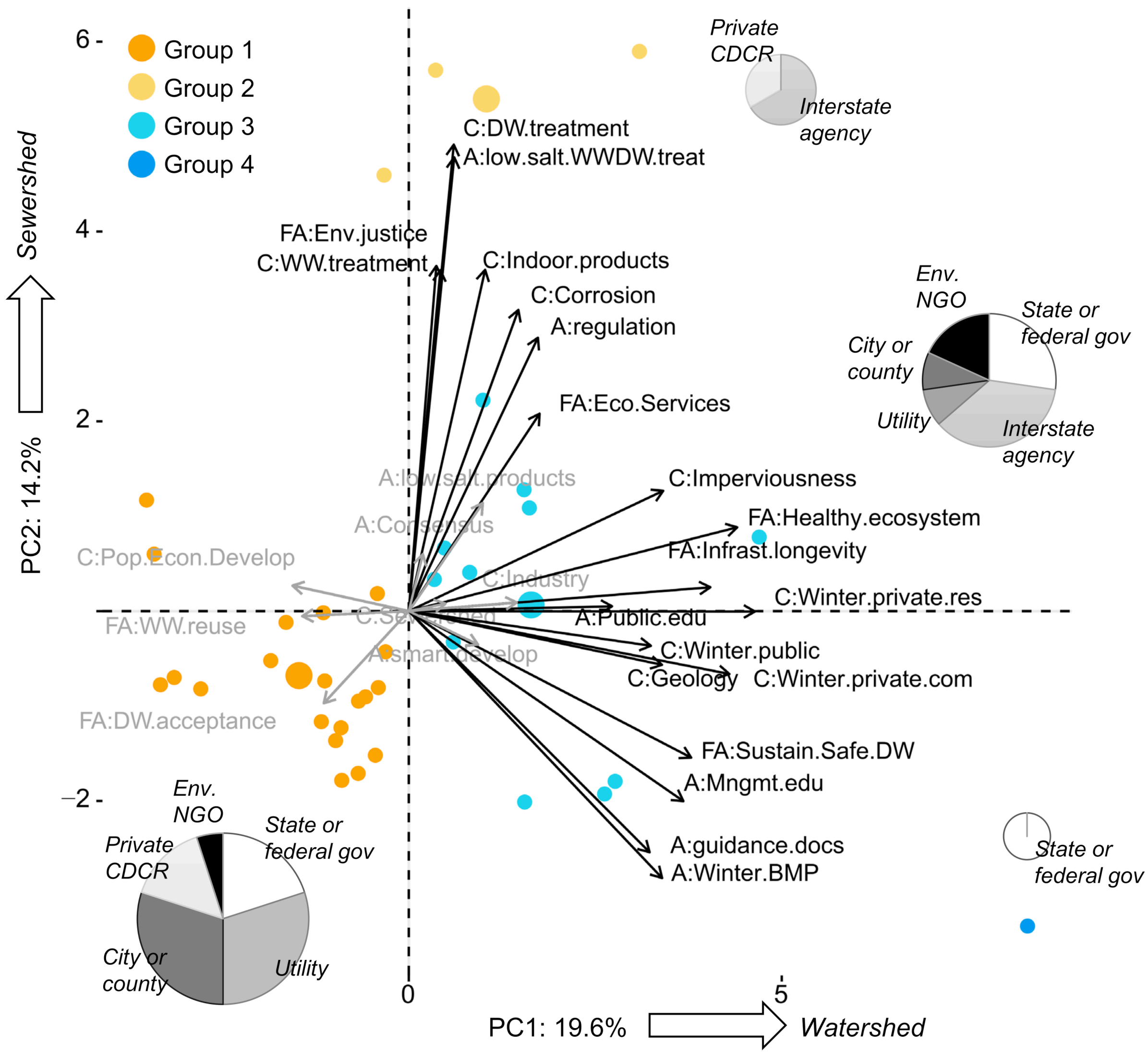
(86% of models); industrial discharges to reservoir tributaries and the sanitary sewer system (74% of models); and down-the-drain disposal of products used in homes, which ultimately flow through UOSA into the reservoir (57% of models). Frequently mentioned impacts of freshwater salinization included ecosystem health (94% of models); sustainability, reliability, and safety of the drinking water supply (89% of models); longevity of urban infrastructure such as pipes, roads, and bridges (66% of models); and the continued practice of indirect potable reuse (51% of models). Frequently mentioned actions that could be taken to address salinization included the creation and adoption of best management practices such as processes, technologies, and training for winter salt application and storage (89% of models); guidance documents for winter maintenance activities (71% of models); imposition of ion-specific regulations such as total maximum daily loads (63% of models); public education focused on reducing salt pollution (74% of models); and the adoption of low-salt products for indoor and outdoor use (63% of models). Across all FCMs, only one concept was considered important by everyone: salts added by winter maintenance activities in the public sector.

Common associations between concepts (i.e., that appeared in > 25% of stakeholder models) are also illustrated in Fig. 2. Not surprisingly, stakeholders frequently linked winter maintenance activities (by public agencies, private companies, and residential communities) to elevated impervious area in the watershed (as a primary driver), as well as to best management practices, guidance documents, and the adoption of low-salt alternative deicers (as potential actions that could be taken to reduce salinization; blue connections in Fig. 2). Regulation, public education campaigns, and controls on population and economic development were frequently mentioned as ways to reduce salt loads from both the watershed (e.g., winter maintenance activities) and sewershed (e.g., down-the-drain disposal of salt-containing products; green connections in Fig. 2).

Four stakeholder groups with significantly different perceptions of the social-ecological system

PCA and hierarchical cluster analysis were used to identify groups of stakeholders with significantly different perceptions of the SES for freshwater salinization that could represent barriers to collective action or opportunities for shared learning. Only two PCs were significantly different than random, collectively explaining ~34% of

Fig. 3. Biplot of weighted degree centrality of salinization concepts. The first principal component (x-axis) separates out individuals that prioritize concepts related to the watershed, and the second principal component (y-axis) separates out individuals that prioritize concepts related to the sewershed. Black vectors and text indicate concepts that contribute significantly to either principal component at a 95% confidence level. Grey vectors and text indicate concepts that do not contribute significantly to either principal component at a 95% confidence level. Prefix codes C, FA, and A indicate concepts that are causes of salinization, factors affected by salinization, and mitigating actions, respectively. Stakeholders with significantly different perspectives about freshwater salinization (i.e., located in different regions of principal component space) are indicated using small colored points. A single large point indicates the median perspective of each group. Pie charts (sized to reflect the number of stakeholders in each group) illustrate the group's professional composition. Additional abbreviations not already described in Fig. 2 include: Sustain = sustainable, Infrast = infrastructure, Eco.Services = ecosystem services, Env.justice = environmental justice, Mngmt = management, edu = education, NGO = nongovernmental organization, and CDCR = private corporations, developers, consultants, and research agencies



the variance in centrality of salinization concepts across mental models (Fig. 3). The first PC (PC1, 19.6% variance explained) captures the perceived contribution of winter maintenance activities to salinization of the Occoquan Reservoir and actions that could be taken to address them (positive PC1: winter maintenance is emphasized, negative PC1: winter maintenance is deemphasized). The second PC (PC2, 14.2% variance explained) captures the perceived role of the sewershed in reservoir salinization, specifically whether salt discharges from UOSA contribute (positive PC2) or do not contribute (negative PC2) to the problem.

Hierarchical clustering with respect to these PCs yields four statistically distinct groups of FCMs. Group 1 includes the largest number of stakeholders (20 of 35; orange circles in Fig. 3) and is dominated by employees from public utilities and city or county government agencies. Group 2 (11 of 35; teal circles in Fig. 3) is dominated by employees from federal, state, or interstate agencies. Group 3 (yellow circles in Fig. 3) consists of two individuals from an interstate agency and one from a private corporation. Group 4 (blue circle in Fig. 3) consists of a single individual from a state or federal agency. All groups excepting Group 4 contain stakeholders with different professional backgrounds, and all professional backgrounds are represented in more than one group (pie charts in Fig. 3), suggesting that differences in how the SES is perceived are not profession specific.

Group-specific social-ecological system networks

Individual mental models belonging to each of the groups were aggregated (see *Methods*) to highlight salinization concepts common to each group. The aggregate model for Group 1 contains the most salinization concepts (C) and relationships (R; 39 C, 177 R; Fig. 4a), followed by the aggregate models for Group 3 (30 C, 127 R; Fig. 4b), Group 2 (29 C, 78 R; Fig. 4c), and Group 4 (19 C, 52 R; Fig. 4d).

The Group 1 aggregate model deemphasizes two causes of salinization (salts added by winter maintenance chemicals in private commercial and residential sectors), two factors affected by salinization (infrastructure longevity and ecosystem health), and one mitigating action (development of regulatory frameworks for salt; Fig. 4a). Group 3 emphasizes the importance of guidance documents for managing salt as well as all concepts deemphasized in Group 1 except ecosystem health (Fig. 4c). Group 4 is similar to Group 3 in its emphasis on salts added by winter maintenance activities in the residential sector. However, it also emphasizes salts contributed by local geology, education and outreach programs (both for the general public and for management), ecosystem health, and the sustainability, reliability, and safety of drinking water supply, concepts that are not emphasized by other groups (Fig. 4d). Group 2 is unique in its emphasis on environmental justice, adoption of low-salt technologies for water and wastewater treatment, and three causes of salinization (salts added by indoor products discharged to UOSA's sewershed, salts added as part of drinking water treatment, and salts released by urban infrastructure corrosion; Fig. 4b).

Focusing on the causes of salinization that each group felt are important, it becomes clear that Groups 1, 3, and 4 are more watershed focused, differing mainly in their degree of emphasis (Fig. 4c,d) or de-emphasis (Fig. 4a) on private sector use of deicers and anti-icers (see quotes Q13 and 14 for context, Table 1). In contrast, Group 2 is more sewershed focused (Fig. 4b). Stakeholder narratives (collected during FCM interviews) suggest that Group 2's sewershed focus may reflect concerns about the prevalence of salt-containing products available for in-home use (Q18, Table 1) and the quantities that are used (Q19, Table 1), as well as the cyclical nature of indirect potable reuse in the Occoquan, wherein salt in surface water enters drinking water systems, moves through homes and businesses into the wastewater collection system, and from there passes through wastewater treatment plants back into surface waters (Q17, Table 1).

Notably, the preferred mode of governance of the Occoquan SES also differed by stakeholder group, with top-down regulatory action being advocated by Group 3 and collective action being advocated by Group 1 (Fig. 4a,c). Stakeholder narratives suggest that preferences for regulatory frameworks are driven by prior experience with this governance model (Q4, Table 1), cynicism about the likelihood of success of other models (Q5, Table 1), and perceptions about who needs to be regulated, for example, industry, where regulation is a standard approach (Q3, Table 1). Preferences for non-regulatory modes of governance appear to reflect strong advocacy for stakeholder-driven, bottom-up approaches (Q1, Table 1) and concerns about the feasibility of regulating certain salt sources, specifically, in-home products (Q2, Table 1).

Perceived contribution of different salt sources

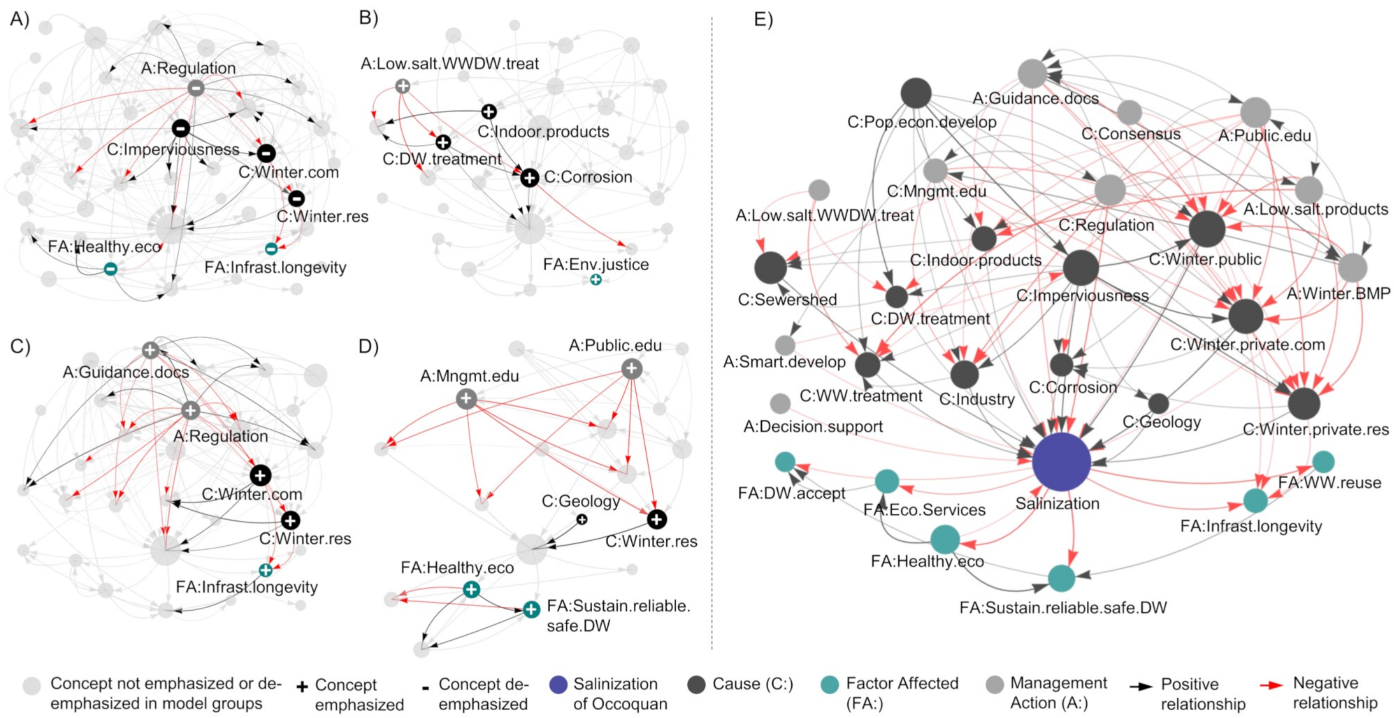
To evaluate the perceived contribution of different salt sources to salinization of the Occoquan, dynamic simulations of various salt-loading scenarios were performed using individual stakeholder FCMs, the four aggregated group models, and a single cross-group "collective model" (Fig. 4e) prepared by taking the median of the aggregated group models (see *Methods*). Dynamic simulations illustrate that salt sources in the watershed (such as winter maintenance activities) were perceived to contribute more to reservoir salinization than salt sources in the sewershed (dark grey vs. black bars in Fig. 5a). This pattern is most evident for the Group 3 model and the average taken across all individual mental models, followed by the Group 4 model, and the collective model. Only models for Groups 1 and 2 predicted that salt contributions from the sewershed and the watershed were comparable.

The relative importance of specific salt subsources (i.e., sources that together comprise total sewershed or total watershed salt loads) also differed by FCM. Typically, salts added by winter maintenance activities had the most impact on salinization, followed by in-home products and industry, other watershed sources (i.e., local geology, agriculture, and infrastructure corrosion), and salts added by water and wastewater treatment (Fig. 5a). An extreme version of this pattern is evident in the Group 4 model, in which salts added by water and wastewater treatment are entirely absent (Fig. 5a). The Group 1 model differs from the other models in that salts added by in-home products and industry were perceived as having the most impact on salinization. The Group 2 model also differs from other models, with water and wastewater treatment perceived to contribute more salts to the reservoir than do local geology, infrastructure corrosion, or agriculture.

Benchmarking perceptions with biophysical measurements

The ratio of sodium mass load from the sewershed (UOSA) vs. watershed (Bull Run + Occoquan River) spans three orders of magnitude during low, median, and high flow conditions, from 0.02 (the watershed contributes 46-times more sodium to the reservoir than the sewershed) to 17.3 (the sewershed contributes 17-times more sodium to the reservoir than the watershed; Fig. 5b). Sodium loading to the reservoir is dominated by outflow from UOSA during low flow conditions (i.e., during dry weather; mean sewershed to watershed ratio: 2.6) and by the watershed during high flow conditions (mean ratio: 0.20). During median flow conditions, the contribution of these two sources is relatively even (mean ratio of 0.75; Fig. 5b).

Fig. 4. Fuzzy cognitive maps (FCMs) of freshwater salinization for stakeholder groups 1 through 4 (A–D) and a collective FCM that represents the median perspective across all four groups (E). Only salinization concepts that were significantly emphasized (plus sign) or de-emphasized (negative sign) in model groups are highlighted in panels A–D ($P < 0.01$). All relationships are shown for the collective model in panel E. Causes of salinization (C) are in black, factors affected by salinization (FA) are in teal, mitigating actions (A) are in dark grey, and the central concept "Salinziation of the Occoquan" is in blue. Negative relationships between concepts are shown using red arrows, and positive relationships are shown using black arrows (arrow width indicates relationship strength). Abbreviations not indicated in prior figures include: Healthy.eco = ecosystem health, and Smart.develop = smart growth and development.



These biophysical estimates were compared to stakeholder perceptions about the relative importance of sewershed and watershed salt sources estimated using our dynamic FCM simulations. Only two sewershed-to-watershed salt ratios from individual stakeholder FCMs (small grey dots in Fig. 5b) fell outside the estimated range (i.e., 94% of individual FCMs are consistent with estimated salt loading from the sewershed and watershed). Most simulations conducted using individual FCMs (21) are consistent with median flow conditions (i.e., fall under the black distribution in Fig. 5b), followed by high flow conditions (11) and low flow conditions (1; Fig. 5b). When individual mental models are averaged or aggregated, the resultant sewershed to watershed ratios are generally consistent with median flow conditions in the Occoquan reservoir (note the positioning of Groups 1 through 4, the collective FCM, and the mean of individual stakeholder FCMs in Fig. 5b). Of these models, the collective FCM appears to best approximate the average sewershed-to-watershed sodium ratio during median flow (black vertical line in Fig. 5b).

DISCUSSION

It is often challenging to identify key drivers, impacts, and potential outcomes of different management approaches for emerging environmental problems where the SES is not well characterized. Our results suggests that FCMs can be an effective tool for: (1) characterizing individual and collective models of the SES; (2) articulating common (Fig. 2) and divergent (Figs. 3 and 4) viewpoints that could be opportunities for collaboration or shared learning experiences, respectively; and (3) comparing SES perceptions to biophysical estimates (Fig. 5), furthering the ability to discuss understanding in context with biophysical conditions. This utility makes FCMs a useful and much needed tool for rapidly coalescing knowledge about emerging environmental challenges and generating systems-level information that can guide future research and collective management efforts.

Areas of agreement and disagreement: implications for collective management

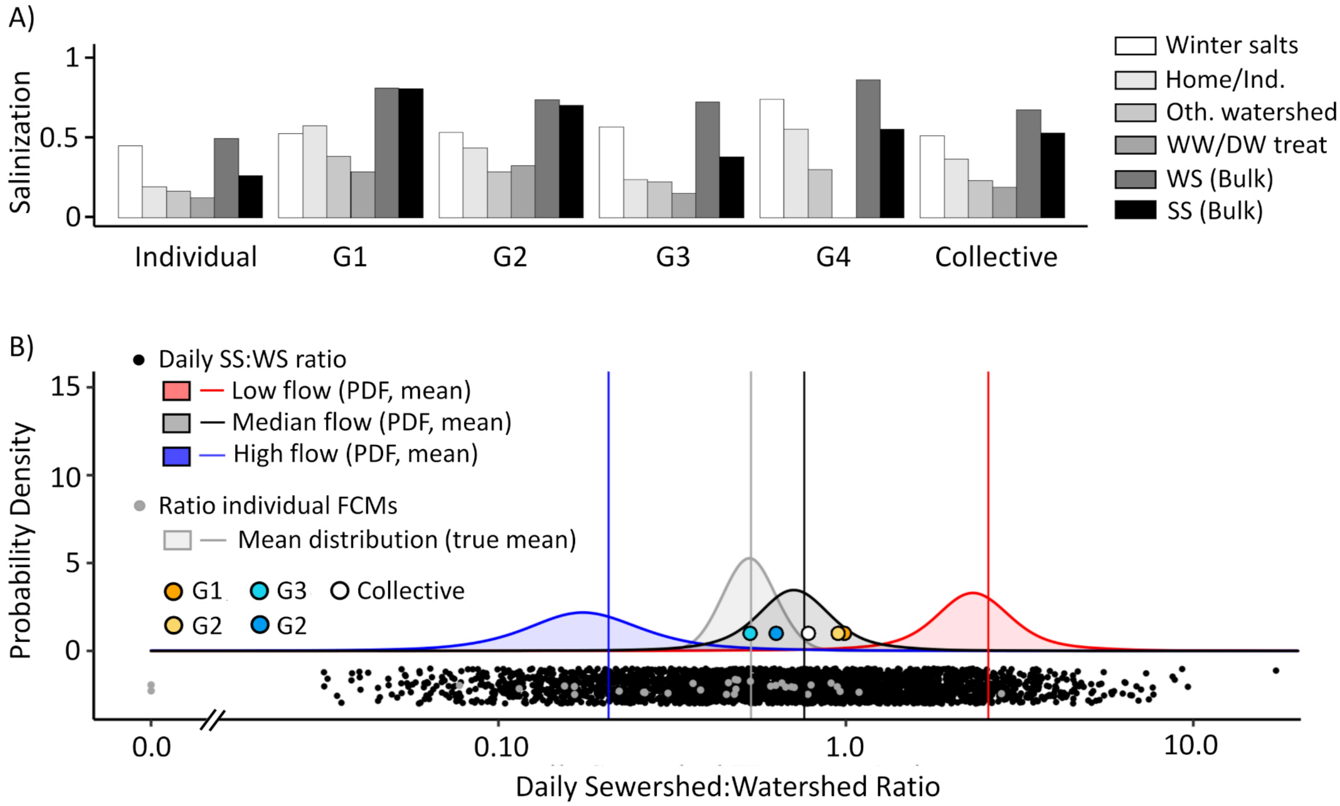
Mode of salt governance

Stakeholder FCMs reveal different perspectives about the importance of top-down regulatory control of salinization vs. bottom-up, voluntary measures. These stances may seem opposing, with regulation appearing to obviate the need for voluntary collective action to manage salt, but this is not really the case. Polycentric, collaborative governance arrangements can emerge through bottom-up collective action or state-centered policy processes, either by design (e.g., intentional decentralization) or institutional layering, as new policy venues and rules are gradually introduced (Langridge and Ansell 2024). In the Occoquan, many existing collaborations between utilities, counties, and other agencies are actually rooted in policy (e.g., the Occoquan Policy), which created

Table 1. Narrative context for mental model groups.

Concept name	Model	Q#	Narrative description
			Actions
Regulation	G1 (-)	Q1	"The most important first step is to build consensus on stakeholder-driven salt and/or ion thresholds that would support salt management strategies without top-down regulation (e.g., without total maximum daily loads). ... Without agreed-to ion or salt concentration goals that are based on good science and widely accepted practice in the water industry, it will be very difficult to make any headway...." [5]
	G1 (-)	Q2	"I'm very skeptical about regulating citizens at home, what they're going to be using in their personal products and so forth; that seems like a huge, huge hurdle." [39]
	G3 (+)	Q3	"After recognizing that it was coming from wastewater and industry, if that's true, then I think there's an element of regulation that has to be involved." [30]
	G3 (+)	Q4	"You know, as a public entity, it's not that I want to be regulated, but it's very effective" [11]
	G3 (+)	Q5	"I think the focus on regulatory frameworks for salt... I think that should be included." Are you thinking more on the top-down total maximum daily load side or the bottom-up management side? "I guess I'm too cynical, I'm thinking top-down regulation." [10]
Low-salt treatment	G2 (+)	Q6	"So, the easiest would be 'focus on low-salt water and wastewater treatment'.... I think that would be high [impact], probably a 0.9 [out of one]." [9]
Guidance documents	G3 (+)	Q7	"Pro guidance, pro regulation, you know, those things [have] an ability to impact inputs of salts, whether it's from runoff in the commercial sector, the private sector, that kind of thing." [36]
Education and outreach (managers)	G4 (+)	Q8	"It's the educational awareness and outreach, I think that's important not only for the public at hand but also for our political leaders, the County supervisors, [and] the board members to understand [this issue] as well." [7]
Education and outreach (general public)	G4 (+)	Q9	"When you're dealing with homeowners, I think education is all you can really do." [38]
	G4 (+)	Q10	"That education, awareness, and outreach goal has to be carefully modified and communicated properly, because I think out of all this research, that's going to be the most important goal that comes out of there in how this research actually changes people's thought process and lives." [1]
	G4 (+)	Q11	"I really agree with identifying the public as part of that education awareness. That's really important ... All of us have a salt footprint, so to speak, in the watershed." [34]
			Causes
Salts added by winter maintenance (private commercial)	G1 (-)	Q12	"I still think that public gets treated more than private, I'm thinking roads, right, road salts is the big one." [20]
	G3 (+)	Q13	"A lot of what's contributing to this, really, is on the private side. The private sector's probably contributing more to this from, call it a parking lot standpoint, as [a] non-point source, and residential to a degree. But I think you'll find there's a heck of a lot more parking lot potentially than there is road." [31]
Salts added by winter maintenance (private residential)	G1 (-)	Q14	"A lot of that is roof, not too many people sprinkling salt on there. ... You won't get as much impact from a homeowner as you would from a private business owner." [5]
	G3,4 (+)	Q15	"We have a lot of private applications that are going on through, you know, all of the private residences... So, it's just not VDOT [Virginia Department of Transportation]. It's a much larger source." [29]
Salts added due to urban infrastructure corrosion	G2 (+)	Q16	"We know that there is a certain a certain amount of the ions that we're seeing as a result of all the decaying concrete in the watershed. Whether that be a building, or a road, or any infrastructure." [39]
Salts added as part of drinking water treatment	G2 (+)	Q17	"Salts added during the treatment of drinking water eventually does impact what is being discharged from the treated wastewater after it goes through people's bodies and heads into the sewer." [1]
Salts added to the sewer from indoor use of cleaning, personal care products, and water softeners	G2 (+)	Q18	"Every time I go to the grocery and go to the detergent aisle, I get a shiver because everything in that detergent aisle is going to be sent to UOSA [Upper Occoquan Service Authority], it's all heading to the sewage plant. Likewise, when I go to the next aisle and it's personal care products and pharmaceuticals and all that stuff is heading to the sewage plant [too]." [39]
	G2 (+)	Q19	"When you look at the amount of salt in those 60-pound bags that we put in those softeners, unless you are using potassium, which is about five times as much and people don't do, that is a ton of salt per house. That's more than the salt you are putting on your sidewalk and driveway every year." [35]
Salts added by local geology	G4 (+)	Q20	"Yeah the Triassic basin has a lot of salts in it ... We've looked at conductivity in Cub run and its off the charts, and we assumed that a lot of it is due to geologic sources, particularly the phosphorus, because they are lakebed sediments and they are eroding." [35]
			Factors affected
Healthy ecosystems (aquatic and terrestrial)	G1 (-)	Q21	"I don't know that there's any impacts [on aquatic life] right now. I haven't seen them." [5]
	G4 (+)	Q22	"I think [the impact of salinization on aquatic life] is going to be really high, because if you exceed the threshold of whatever the species is then it can't make it unless they're sort of salt tolerant." [16]
Infrastructure longevity (the lifetime of pipes, concrete, or metal structures)	G1 (-)	Q23	"I am consciously choosing not to include infrastructure longevity because I don't believe that the change of salt levels from 20–30 mg/L has a meaningful impact on corrosion of the distribution system or any concrete structures embedded in the Occoquan watershed." [7]
	G3 (+)	Q24	"If you want infrastructure to last long, you want to have less salinization. Obviously, the infrastructure is not going to last long if it gets corroded faster." [1]
Environmental justice	G2 (+)	Q25	"This is about equitable access to water. It [salinization] will make it harder...." [15]
Sustainable, reliable, and safe drinking water supply for people	G4 (+)	Q26	"That seems like the primary goal, you know, safe clean water" [31]

Fig. 5. (A) Perceived salinization (relative scale) from the overall watershed (dark grey), overall sewershed (black), and contributing subsources, including winter maintenance chemicals (white), in-home products and industry (lightest grey), other watershed sources such as local geology, infrastructure corrosion, and agriculture (light grey), and water and wastewater treatment (medium grey). Results are shown for individual fuzzy cognitive maps (FCMs; average scores), FCMs for stakeholder groups 1 through 4, and the collective FCM. (B) Sewershed (SS) to watershed (WS) salt ratios, including estimated daily ratios for the Occoquan Reservoir (small black dots), perceived ratios from individual FCMs (small grey dots), ratios for group FCMs (G1: orange dot, G2: yellow dot, G3: light blue dot, G4: blue dot), and the ratio for the collective FCM (white dot). The mean perceived SS-to-WS ratio estimated from individual FCMs (vertical line) and the probability distribution about that mean (shaded region) are shown in grey. Predicted ratios for the reservoir during low (red), median (black), and high (blue) flow conditions are shown using shaded probability distributions, with vertical lines marking the mean of each distribution.



new institutions, a compliance monitoring program, and the multijurisdictional financial arrangements to support it (i.e., there are elements of polycentric governance of water quality in the Occoquan that were instituted top-down; Grant et al. 2022). Although the Policy only addresses regulated contaminants, which many salt ions are not (Schuler et al. 2019), the collaborative arrangements that formed under the Policy have been leveraged to create working groups on salt and other unregulated contaminants, an evolution in line with voluntary, collective action (Langridge and Ansell 2024).

Certain salt-related activities are still catalyzed by regulation. For instance, the 2017 total maximum daily load for chloride in Accotink Creek, located near the Occoquan watershed in Fairfax County, initiated a wave of collaborative activities centered around the development of a salt management strategy toolkit for Northern Virginia (ICPRB and VA DEQ 2020) and may have informed the pro-regulation stance evident in certain stakeholder FCMs (e.g., group 3; Fig. 3c). Other salt-related activities had no regulatory catalyst, including participation in ECOS as part of this Growing Convergence Research Project and the decision to finance a network of continuous monitoring stations for specific conductance (a measure of salinity) in the Occoquan Reservoir. If stakeholders were to co-develop voluntary standards for sodium, as advocated in Group 1 FCMs (see Table 1, Q1), it would be another example of a bottom-up measure. A range of sodium ion standards exist across U.S. states (Schuler et al. 2019) that, in context with health and toxicity studies (Calabrese and Tuthill 1981, Hallenbeck et al. 1981, Welty 1986, Corsi et al. 2010, Khan et al. 2011, Cooper et al. 2014, Clements and Kotalik 2016, Schuler and Relyea 2018; *Canadian Environmental Protection Act, 1999:* https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/publications/canadian-environmental-protection-act-1999.html), could potentially inform the development of local criteria for the Occoquan. FCMs could be used to identify critical stakeholders and decisionmakers who need to be involved in collaborative decision-making about these criteria, supporting a stakeholder or issues analysis (Susskind et al. 1999). They might also be combined with other stakeholder assessment processes (see the Society of Professionals in Dispute Resolution 1997), leading to recommendations regarding: (1) institutional, financial, or other constraints that could limit collaborative problem-solving efforts, and (2) the circumstances under which key parties would agree to participate in those efforts.

Salt sources

From the standpoint of collective management, winter maintenance chemicals appear to be low-hanging fruit, consistent with the attention they are paid in the salinization literature (Godwin et al. 2003, Kaushal et al. 2005, Kelly 2008, Corsi et al. 2015). Co-development of the salt management strategy toolkit for Northern Virginia (ICPRB and VA DEQ 2020) appears to have played an outsized role in shaping stakeholder perspectives about winter maintenance chemicals. Many of the concepts central to the salt management strategy toolkit (e.g., winter best management practices, low-salt products such as alternative deicers, and public education and outreach; ICPRB and VA DEQ 2020) appear frequently in stakeholder FCMs, illustrating the salt management strategy toolkit's contribution to collective learning and shared understanding of freshwater salinization in the region (see Appendix 1 for additional details about the salt management strategy toolkit).

Variability in stakeholder FCMs with respect to the sewershed suggests that the sewershed represents a new frontier for shared learning rather than an area that is already ripe for collective action. Attention to the sewershed has been increasing in the literature, with a variety of studies identifying significant wastewater contributions to freshwater salinization, even in regions where deicing is prevalent (Novotny et al. 2009, Bhide et al. 2021, Overbo et al. 2021). Factoring wastewater into the freshwater salinization story has important environmental and public health implications given the contribution of wastewater to overall stream flow in the United States (at least 10% of the flow in > 25% of U.S. streams is wastewater effluent; Rice and Westerhoff 2017) and the important role treated wastewater is projected to play as a future water source due to water supply shortfalls (GAO 2014, EPA 2019, Martin and Via 2020). Following multiple rounds of FCM interviews and small group FCM discussions, one stakeholder noted, "My greatest knowledge growth or conceptual change [has been] around the wastewater... now I see there are these personal care products and human excretion and industrial [inputs] too..." [stakeholder 7]. This observation suggests that, as much as the sewershed is presently contentious, it is also a frontier for shared learning that participatory modeling tools like FCM might help to facilitate. Next, we address how this learning might occur, focusing on "cheap talk" and perspective-taking.

Fuzzy cognitive maps as tools for facilitating shared learning

Encouraging "cheap talk"

When aggregated to represent collective perceptions, FCMs have the potential to become co-produced boundary objects that facilitate communication across stakeholders from different social worlds (Leigh Star 2010, Black 2013, Huang et al. 2018). In this mode, they may serve as an organizing framework for "cheap talk", i.e., frequent, ordinary, communication that is neither costly nor binding (Farrell and Rabin 1996, Wilson and Sell 1997), about areas where stakeholders disagree. Cheap talk can be a valuable tool for shared learning. It has been shown to foster group identity, facilitate cooperation, and help individuals negotiate jointly beneficial solutions when perspectives differ (Sally 1995, Ostrom 2010*a,b*), as is the case here with the sewershed. Effective cheap talk, however, requires trust; conversations can be nonbinding, but they should not be dishonest (Wilson and Sell 1997). The collective trust and group identity the Occoquan's stakeholders have built though past successful collaborations like the salt management strategy toolkit and other initiatives bodes well for the effectiveness of cheap talk in this system (Kramer and Tyler 1996, Nagendra and Ostrom 2014, Bodin 2017; *Canadian Environmental Protection Act, 1999:* https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/publications/canadian-environmental-protection-act-1999.html). As one stakeholder said, "I, several times, have expressed my confidence in all of our colleagues, and here this morning I hear it. Each organization, for want of better words, upping their game [to manage salt]" [4]. Comments like this illustrate that while stakeholders may not always agree about salt sources, they share a commitment to addressing salinization, making the emergence of collective action a real possibility.

Encouraging perspective-taking

Nearly all stakeholder mental models captured sewershed-to-watershed sodium ratios that fell within the observed range for the Occoquan system during low, median, or high flow conditions (Fig. 5b), which indicates that stakeholder understanding of this dimension of the SES, although variable, was generally high. Because system variability validates a range of possible perspectives on the relative importance of salt sources, it has the potential to focus future discussions on why certain models capture specific conditions well, rather than the identification of a single "best" model. In effect, it may encourage a form of perspective-taking (trying on alternative models and considering their validity), which has been shown to increase collaborative behavior in collectively managed natural resource systems (Wald et al. 2017). Perspective-taking has proven especially beneficial in high-variability systems where management becomes less a search for optimal solutions and more an ongoing process of learning and negotiation (Pahl-Wostl and Hare 2004, Innes and Booher 2018). This may make it particularly appropriate for fostering shared understanding in systems like the Occoquan, where variability in the resource (sodium ion concentrations in the reservoir) informs variability in perceptions of the SES.

Benefits and limitations of fuzzy cognitive maps for understanding the social-ecological system

Several features of FCMs, beyond their ability to identify critical stakeholders who should be involved in collaborative decision-making or facilitate cheap talk and perspective-taking, make them well suited for characterizing SESs and using that knowledge to support collective management of emerging environmental challenges. A subset of these capabilities (and potential limitations) are detailed here. First, the FCM development process is relatively straightforward and engaging, bringing a diversity of perspectives to the table (Özesmi and Özesmi 2004). This characteristic is evident in the fraction of stakeholders willing to develop FCMs in this study (90% of those we contacted) and the time invested in model building (50 min on average for the initial FCM exercise, followed by an additional 1.5 h on average in subsequent meetings to refine concepts, revise models, and validate final FCMs; see Appendix 1).

The iterative nature of FCM development in this study (i.e., the inclusion of review and revision steps) is not standard for the field but appears to have increased the legitimacy of FCMs in the eyes of stakeholders: "The process the team has done, and going through and revising them [the FCMs] and getting more input and going through and revising them again; I think the legitimacy is the best you can possibly do" [10]. This finding is something to consider when using FCMs as a tool for co-producing new knowledge about the form or structure of SESs, where fully incorporating the values and perspectives of different actors involved in resource management is a top priority (Hailu and Tolossa 2020). The time commitment required for cyclical co-production of FCMs, however, can also be a limitation, particularly if the pool of possible actors is large. In such instances, alternative approaches for eliciting FCMs may be more appropriate, for example, group model-building (Martin and Via 2020, Shahvi et al. 2021, Olofsson et al. 2023) or use of survey instruments in lieu of one-on-one interviews to identify concepts and their interrelationships (Özesmi and Özesmi 2004, Nozari et al. 2021, Aminpour et al. 2022).

Another strength of FCMs for understanding SESs is their applicability in systems where information is limited (i.e., where data supporting certain relationships is hard to come by or only available to select experts; Özesmi and Özesmi 2004, Gray et al. 2019). This property can allow stakeholders to make connections they feel are valid, but where the underlying mechanisms are unclear (i.e., "I don't know enough about groundwater, but I'm imagining that it could be directly impacted" [28]). However, it can also become a point of methodological contention, potentially undermining trust (i.e., "I think there is a danger that some of this process is driven entirely by opinions" [9]). Addressing this issue is challenging and may require recurrent discussions of FCM results and approaches in the attempt to acknowledge/resolve methodological concerns and remind stakeholders that FCMs are not intended to be a substitute for physical models. Rather, they are a way to provide a broader systems perspective that incorporates elements such as governance that are typically outside the scope of physical models, facilitating shared learning (Özesmi and Özesmi 2003, Olofsson et al. 2023). Exploring alternative modes of FCM collection that explicitly account for uncertainty (e.g., fuzzy grey cognitive maps or intuitionistic fuzzy cognitive maps; Salmeron 2010, Papageorgiou and Iakovidis 2013) may also help to address stakeholder concerns, providing the means to identify regions of the SES where less is known and the potential for learning is highest.

A final feature that makes FCMs valuable for understanding SESs (both for freshwater salinization and other emerging environmental problems) is their ease of incorporation into the cycles of learning and assessment characteristic of collective management (i.e., each new mental model can build upon the last, creating a dynamic SES; Pahl-Wostl and Hare 2004). This dynamicity is important because SES understanding (particularly of emerging problems) is expected to evolve over time, making recurrent evaluation important (Carley 1997, Schlüter et al. 2014). Our future work will leverage and explore this functionality, improving the ability to treat second-level variables such as understanding the SES as fully dynamic, and expanding knowledge of the role that understanding plays in catalyzing collective management of emerging environmental problems such as inland freshwater salinization.

CONCLUSIONS

We have demonstrated that FCMs can be an effective tool for characterizing stakeholder understanding of freshwater salinization, including key knowledge concepts and how those concepts are linked together into complex SES networks. We illustrate that FCMs can: (1) capture physically meaningful information about the SES (e.g., reproducing realistic sewershed vs. watershed salt source balances), and (2) reveal differences in the perceived importance of individual salt subsources, their societal and environmental impacts, and how they might be managed, that can be used to diagnose areas of agreement where bottom-up management is likely (winter salt sources), as well as divergent views (sewershed salt sources, governance approaches) that could represent barriers to collective action or opportunities for shared learning. The process we describe for upscaling individual knowledge to systems-level understanding is not salt specific and can be used to inform management approaches for other emerging challenges.

Author Contributions:

M. A. Rippy: conceptualization, methodology, investigation, formal analysis, writing – original draft; B. Roston: formal analysis, visualization; E. Berglund: investigation, writing – reviewing and editing; P. Aminpour: methodology, resources; L. Krauss: data curation, formal analysis; S. V. Bhide: formal analysis, writing – reviewing and editing; T. Schenk: conceptualization, writing – review and editing; K. Rowles: conceptualization, writing – reviewing and editing; S. Misra: writing – reviewing and editing; T. Birkland: writing – reviewing and editing; S. Kaushal: writing – reviewing and editing; S. B. Grant: conceptualization, writing – reviewing and editing.

Acknowledgments:

Funding was provided by a U.S. NSF GCR Program (#2021015, 2021089, and 2020820) and by a Metropolitan Washington Council of Government award to S. B. G. and S. S. K. (#21-001). The authors thank members of the Executive Committee on the Occoquan System (ECOS) for their insights and guidance. The authors declare no competing financial or non-financial interests.

Data Availability:

The data and code that support the findings of this study are available on request from the corresponding author, M. A. R. Data and code will only be made available in de-identified forms because they contain information that could compromise the privacy of research participants. Ethical approval for this research study was granted by Virginia Polytechnic Institute and State University's Institutional Review Board (HS #20-648).

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SUPPLEMENTAL INFORMATION FOR

Characterizing the social-ecological system for inland freshwater salinization using fuzzy cognitive maps: Implications for collective management

Table of Contents

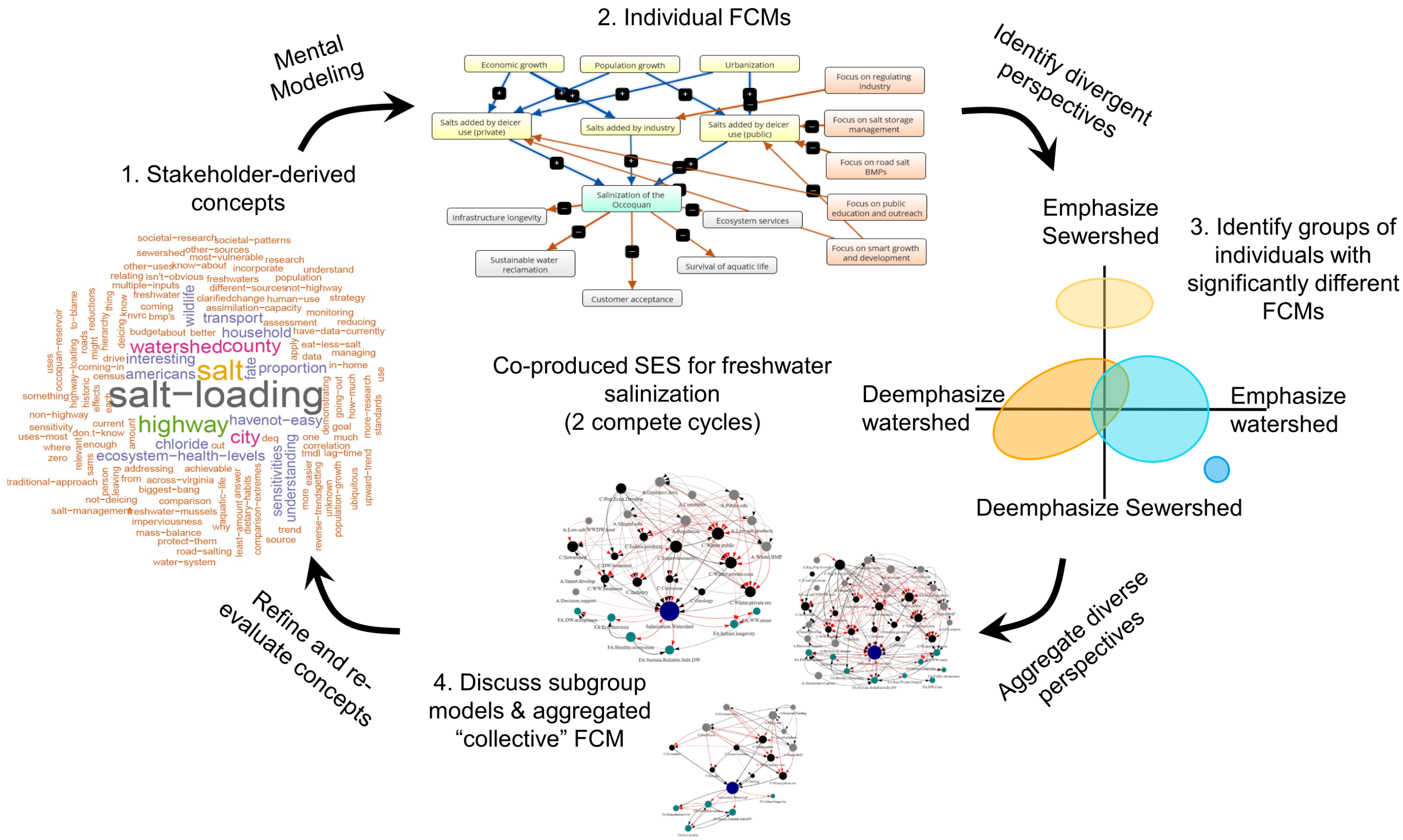
TABLES – reproduced exactly as shown to stakeholders

TABLE 1: Concepts that contribute to salinization of the Occoquan reservoir and tributaries	
Concept Abbreviation	Concept Definition
Salts released from industry *(e.g., discharge of salts from manufacturing)*	Discharge of salts to the sewage collection system or to streams in the Occoquan watershed from manufacturing and other industrial sources
Salts added to the sewer by food/human excretion	Salts discharged to the sewage collection system from human urine or feces
Salts released from winter maintenance activities (private – commercial entities)	Salts added from the application of anti-icing and deicing agents to roads or parking lots by **private, commercial entities**. *Includes unintended (indirect) application of salts by the way these chemicals are stored and transported*
Salts released from products used outside residences or commercial buildings for purposes other than winter maintenance *(e.g. fertilizers, vehicle cleaning products)*	Salts added from the outdoor application of chemicals for purposes other than winter maintenance (e.g., use of detergents, fertilizers, etc., outside of homes, offices, or commercial buildings)
Salts added during the treatment of drinking water	Salts that are introduced as part of the drinking water treatment process (disinfection, softening, pH control, etc.)
Salts released from local geology	Salts from dissolution of natural bedrock or soils
Impervious surface area	Surfaces that are not permeable to rainfall and that generate runoff, including rooftops, parking lots and roads (a consequence of urbanization)
Salts added to the sewer from use of cleaning and personal care products and water softeners inside residences or commercial buildings	Use and discharge or disposal of salts into the sewer system from cleaning and personal care products and water softeners in homes, offices or commercial buildings (e.g., detergents, soaps, water softening chemicals, etc.)
Salts released from discharge of treated wastewater	Highly treated wastewater discharged by UOSA to Bull Run, a tributary of the Occoquan watershed
Salts released from agricultural activities	Nonpoint source salt inputs due to outdoor application of fertilizer and other chemicals in the agricultural sector
Population and economic development	The number of people that reside in the Occoquan watershed and the size of its economy
Salts added during the treatment of wastewater	Salts that are introduced as part of the wastewater treatment process (chlorination, dechlorination, pH control, etc.)
Salts released from winter maintenance activities (public entities)	Salts added from the application of anti-icing and deicing agents on **public roads (e.g., VDOT)**. *Includes unintended (indirect) application of salts by the way these chemicals are stored and transported*
Salts released from concrete dissolution (urban karst) and infrastructure corrosion	Salts from corrosion of urban infrastructure (including concrete)
Salts released from winter maintenance activities (private – residential entities)	Salts added from the application of anti-icing and deicing agents to roads or driveways by **residential homeowners**. *Includes unintended (indirect) application of salts by the way these chemicals are stored and transported*

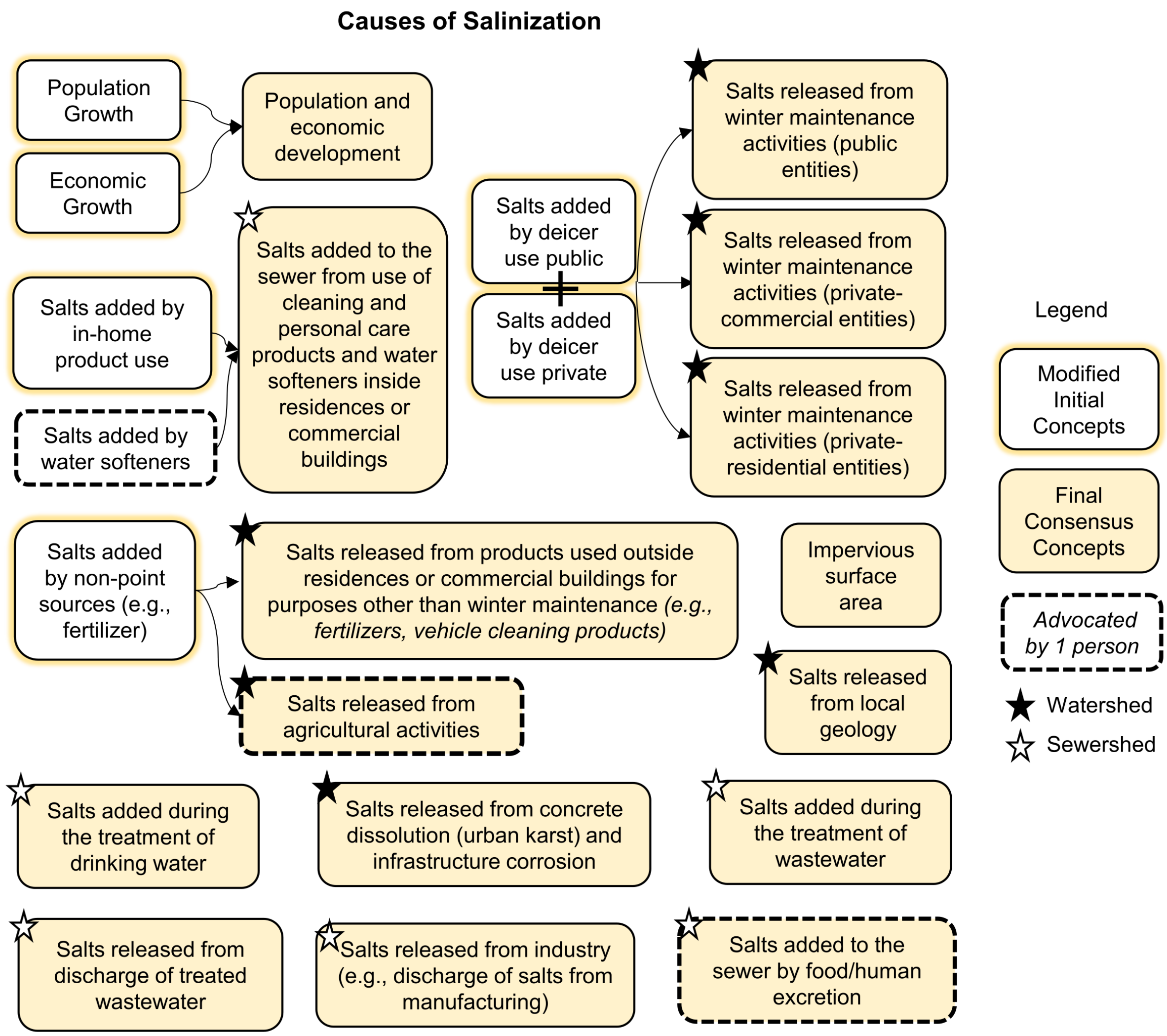
TABLE 2: Factors affected by salinization of the Occoquan reservoir and tributaries	
Concept Abbreviation	Concept Definition
Infrastructure longevity	The lifetime of built infrastructure (e.g., pipes for water and wastewater distribution, concrete or metal structures, etc.)
Reputation of the winter management industry	Public perception of the businesses and agencies that apply salt (e.g., the extent to which they are careful, environmentally conscious, and safe)
Public advocacy for new salt management policies that are not science-based (i.e., reflecting misperceptions, not facts)	New salt management policies are advocated for that reflect incomplete information or a misunderstanding of freshwater salinization, its causes, or its consequences
Environmental justice	Equal access to healthy ecosystems and safe drinking water
Sustainable, reliable, and safe drinking water supply for people	Water in the Occoquan reservoir is safe to drink and protective of the health of individuals with low sodium diets, both in the short (days to years) and long (decades to centuries) term
Healthy ecosystems (water quality is protective of both aquatic and terrestrial species)	Water in the Occoquan watershed is below salt thresholds that cause harm to aquatic and riparian life and can support diverse animals and plants
Cost of remediating legacy salt pollution in the Occoquan watershed	Cost of restoring water quality (e.g., reducing salt concentrations) in the Occoquan watershed to levels that are protective of pubic and ecosystem health
Soil quality in the Occoquan watershed	The quality of watershed soils (e.g., sodicity and infiltration, ion-specific toxicity, availability of essential nutrients, etc.)
Customer acceptance of drinking water	Drinking water is perceived as high quality and safe to drink (relatively few complaints regarding taste, odor, and color)
Cost of drinking water provision	Cost for treating source waters (e.g., water from the Occoquan reservoir) to meet regulatory requirements and perceptual (e.g., taste, odor, and color) goals
Performance of stormwater BMPs	Ability of stormwater BMPs to effectively capture/infiltrate runoff and remove pollutants
Benefits (beyond water supply) that people derive from healthy ecosystems	The variety of ecosystem services provided by the Occoquan reservoir and its tributaries beyond drinking water supply, including but not limited to scenic views, recreation (fishing, birding), nutrient cycling, and sequestration of nutrients such as N and P in reservoir sediments
Public awareness of environmental impacts of freshwater salinization	Public awareness of the impact salinization may have on human and ecosystem health
Sustainable water reclamation (e.g., wastewater reuse)	Discharge of highly treated wastewater to the Occoquan reservoir to maintain/augment local drinking water supplies

TABLE 3: Actions that can mitigate the risk of salinization of the Occoquan reservoir and tributaries	
Concept Abbreviation	Concept Definition
Focus on consensus building	Collaboration and consensus building among diverse stakeholder groups
Focus on decision support tools to inform winter-specific and year-round salt management	Implementation of decision support tools for managing multiple ions from multiple sources *(e.g., models, benefit-cost analysis, life cycle analysis).* Includes, but is not limited to decision support for winter salt management
Focus on regulating population growth in the watershed	Implement population management strategies geared towards regulating future population growth (e.g., family planning initiatives, restrictions on new residential development, etc.)
Focus on smart growth and development strategies *(new development & redevelopment)*	Implement smart growth and development strategies in the Occoquan watershed that are designed to reduce salt discharge to sewers and streams. Includes new development as well as urban redevelopment. Emphasis is on smart growth rather than restricting growth
Focus on regulatory frameworks for salt *(e.g., TMDL or similar)*	Salt regulatory frameworks (ion criteria, Total Maximum Daily Load (TMDL) salt use restrictions). Top-down regulation and enforcement of salt standards. Restrictions on point and nonpoint source salt discharge
Focus on low-salt treatment processes and technologies for water and wastewater treatment	Adoption of low-salt water and wastewater treatment processes and technologies *(e.g., wastewater UV disinfection in place of chlorination)*
Focus on low-salt products for indoor and/or outdoor use	Adoption of low-salt products for indoor and/or outdoor use (e.g., behavior change). This includes use within or outside homes, offices, or commercial buildings or on roads, driveways, and parking lots to reduce salt inputs to domestic wastewater or the watershed
Focus on establishing a body of experts to help mitigate salinization	An oversight body of experts that can inform decision making about salinization and approaches to manage it in the Occoquan watershed
Focus on salt action plans and management protocols *(guidance docs for winter-specific and year-round management)*	Salt action plans, including source and land-use specific management and reduction protocols as well as effectiveness monitoring. This includes, but is not limited to, winter salt management plans
Focus on BMPs for winter maintenance by public, private-commercial or private-residential entities *(e.g., for salt application, storage, training and certification)*	Implementation of BMPs (processes, technologies, or training) for winter salt management by public, private-commercial or private-residential entities. Includes best practices for anti-icer and deicer application and salt storage management as well as training/certification for both application and management. *Could involve implementing the SaMS toolkit*
Focus on capturing low-salinity stormwater *(e.g., Vulcan quarry)*	Develop the capacity to store low salinity stormwater in the Vulcan quarry (e.g., work towards the creation of alternative, low-salt water sources)
Focus on reducing the public's level of service (LOS) expectations during/after winter storms (e.g., bare pavement expectations)	Work to moderate the public's level of service (LOS) expectation of clear drivable roads immediately after storms. Promote new norms for winter driving behavior
Focus on stakeholder-driven ion thresholds to support salt management without top-down regulation (e.g., without TMDLs)	Stakeholder driven water quality guidelines for salt ions (establish thresholds of acceptability for the Occoquan reservoir and its tributaries)
Focus on public education and outreach *(kindergarten to adult, year-round and winter-specific content)*	Public education and outreach about salinization tailored for a range of age groups *(what salt is, consequences of salinization, costs of management alternatives, salt use guidelines by season, etc.)*
Focus on funding to support ongoing salt research *(emphasis on fate and transport)*	Develop ongoing funding programs to support research on salt fate and transport mechanisms
Focus on education and outreach to managers *(year-round and winter-specific)*	Education and outreach programs featuring year-round and season-specific content intended for political leaders, land managers, county supervisors, board members, and other management/governance entities

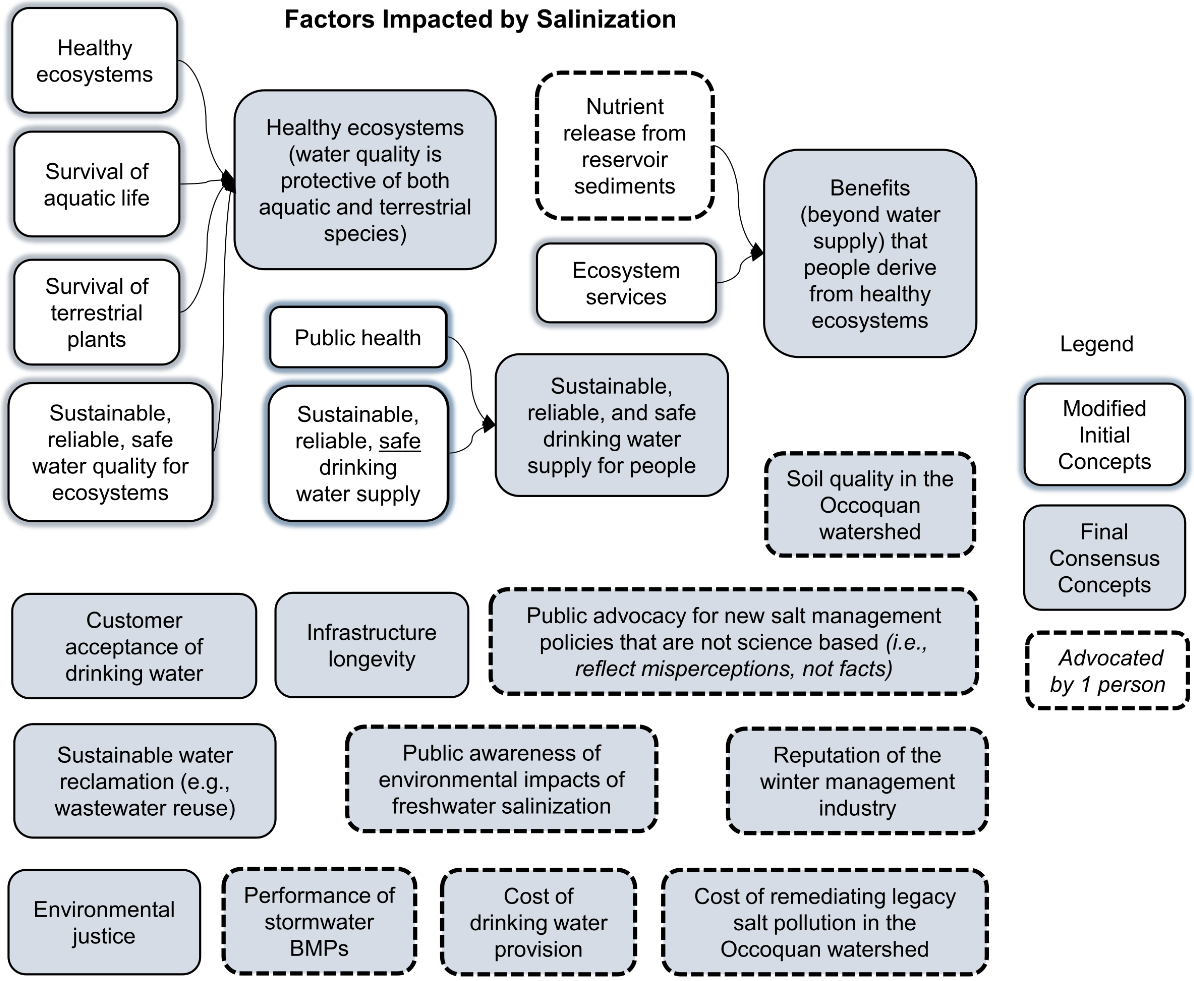
FIGURES



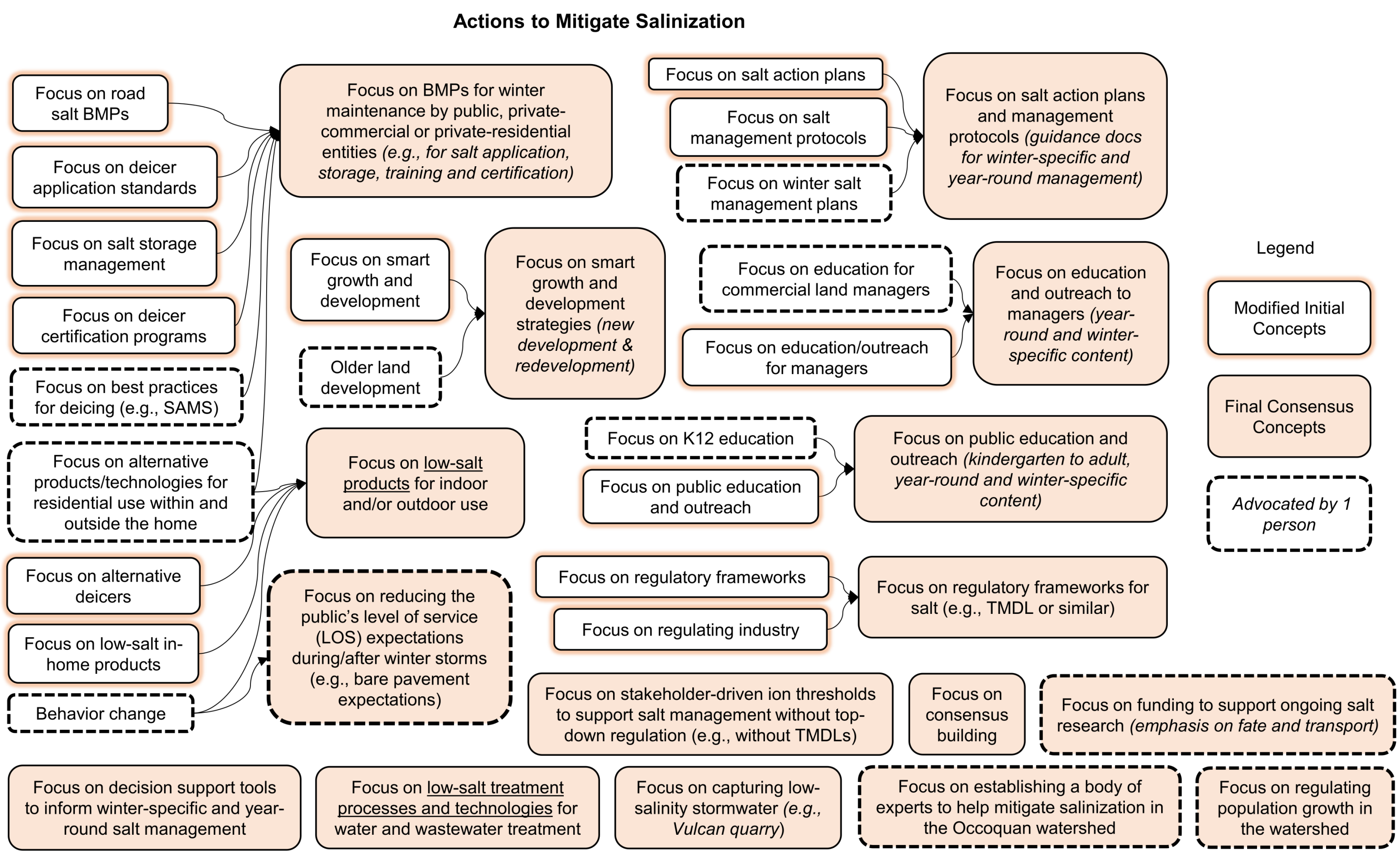
Supplemental Figure 1: Cyclical process of SES co-production. Each cycle includes 1) generation of stakeholder-derived salinization concepts (causes, consequences, and mitigating actions), 2) generation of individual FCMs, 3) identification of stakeholders with significantly different perspectives, 4) small group discussion/evaluation of group and collective mental models of the SES, and 5) concept refinement and re-evaluation based on small group discussions. The individual, group, and collective FCMs evaluated in this study are the result of two iterations through this cycle.



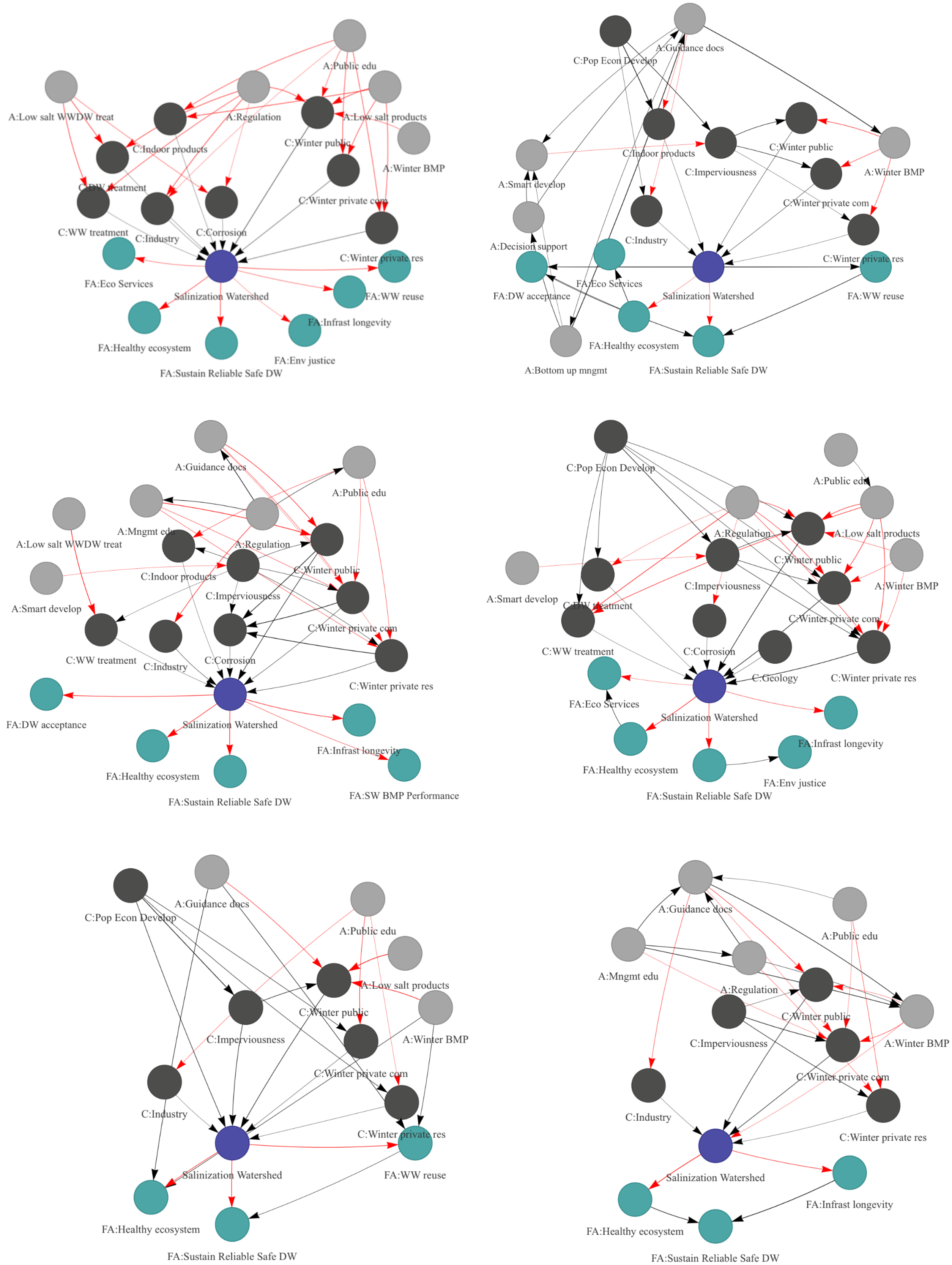
Supplemental Figure 2: Flow chart illustrating how concepts pertaining to causes of freshwater salinization have been consolidated and revised based on feedback from ECOS members during initial FCM interviews and small group discussions (see Supplemental Figure 1). Concepts with white (yellow) backgrounds represent initial (final) causes of freshwater salinization. New causes (added de-novo by a single stakeholder) are shown using black dashed borders. Causes are marked with a white (black) star when they primarily reflect sewershed (watershed) salt inputs.



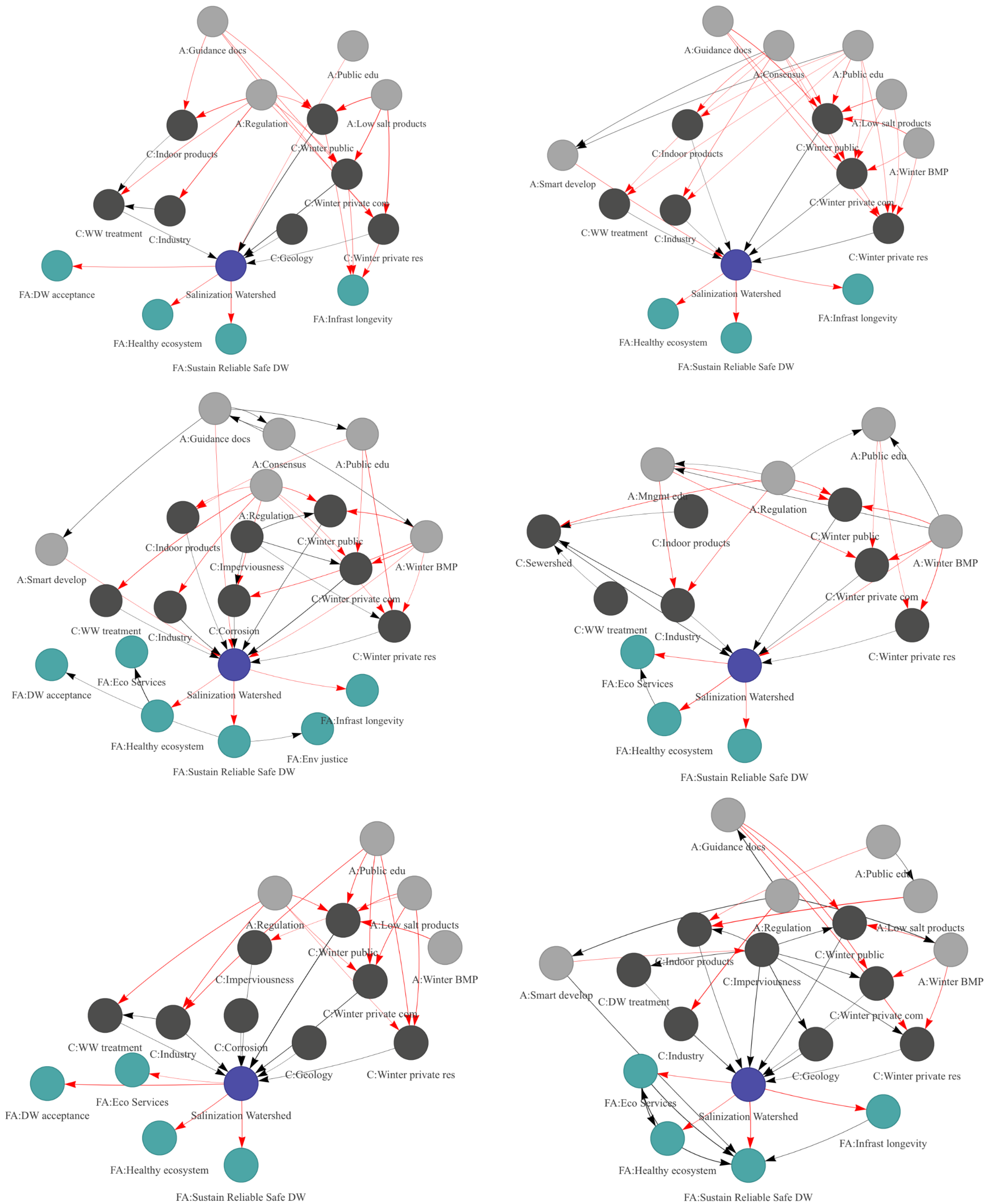
Supplemental Figure 3: Flow chart illustrating how concepts for factors affected by freshwater salinization have been consolidated and revised based on feedback from ECOS members during initial FCM interviews and small group discussions (see Supplemental Figure 1). Concepts with white (blue) backgrounds represent initial (final) consequences of freshwater salinization. New consequences (added de-novo by a single stakeholder) are shown using black dashed borders.



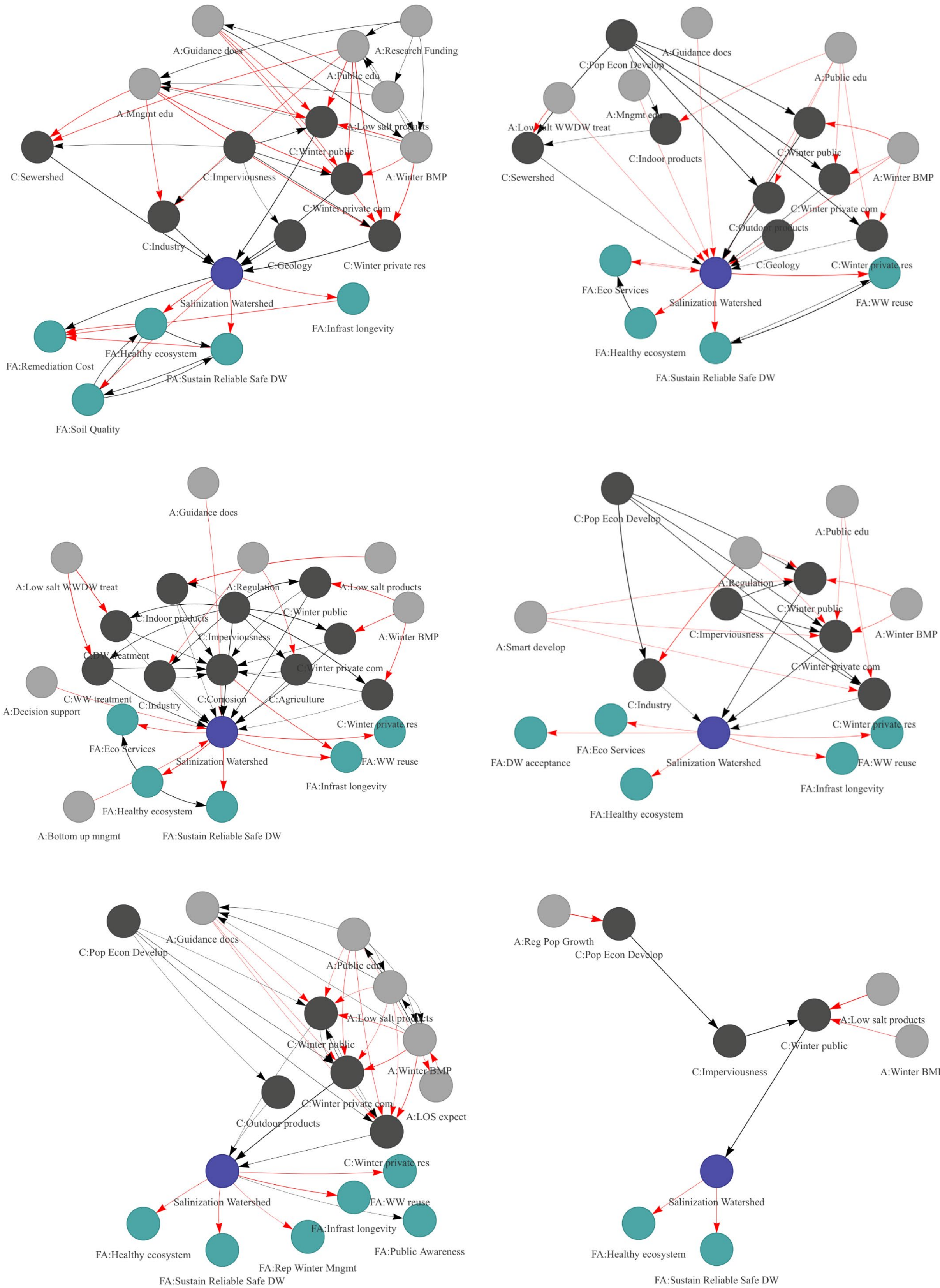
Supplemental Figure 4: Flow chart illustrating how concepts representing mitigating actions have been consolidated and revised based on feedback from ECOS members during initial FCM interviews and small group discussions (see Supplemental Figure 1). Concepts with white (red) backgrounds represent initial (final) actions that can be taken to mitigate freshwater salinization. New consequences (added de-novo by a single stakeholder) are shown using black dashed borders.



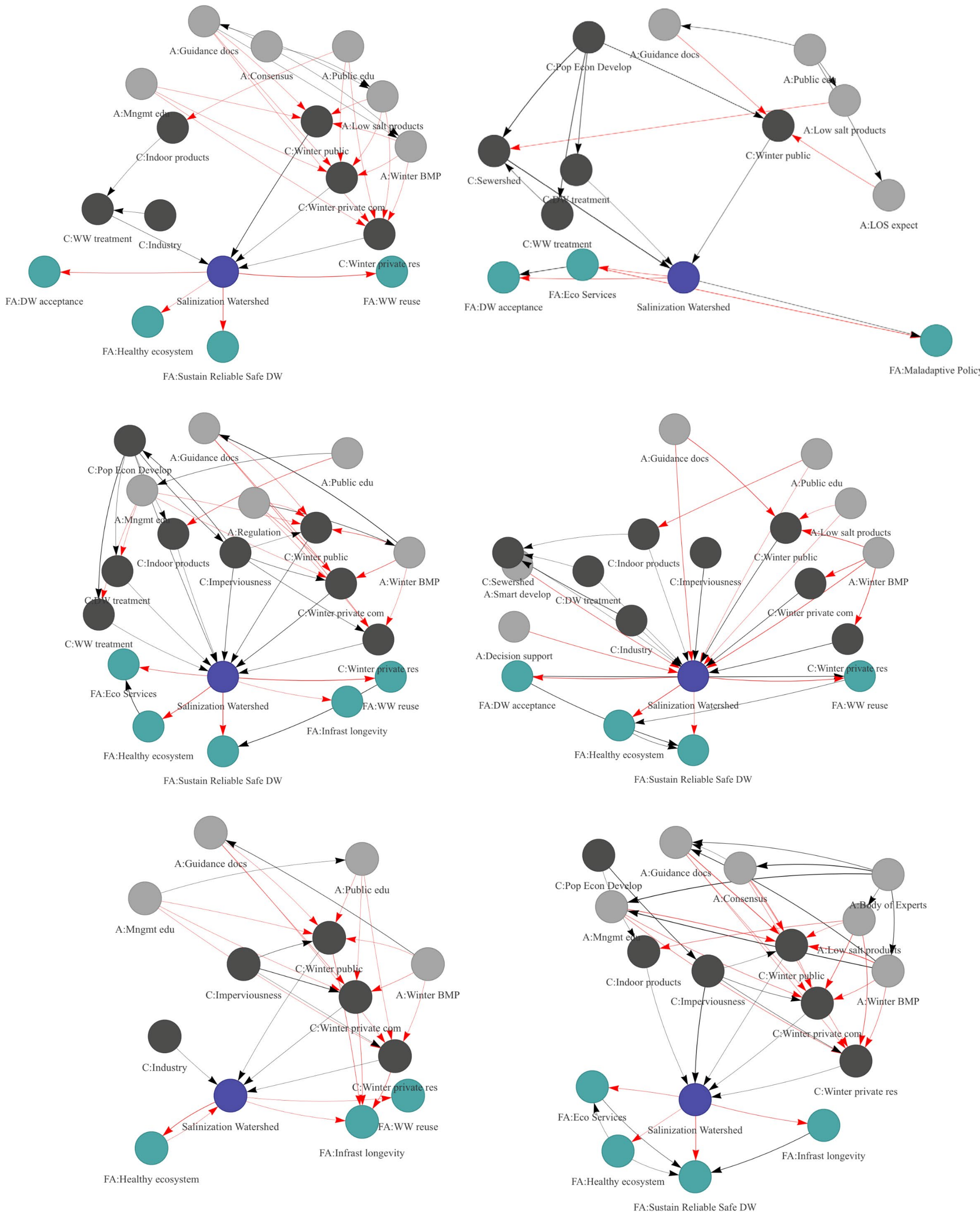
Supplemental Figure 5, Part 1



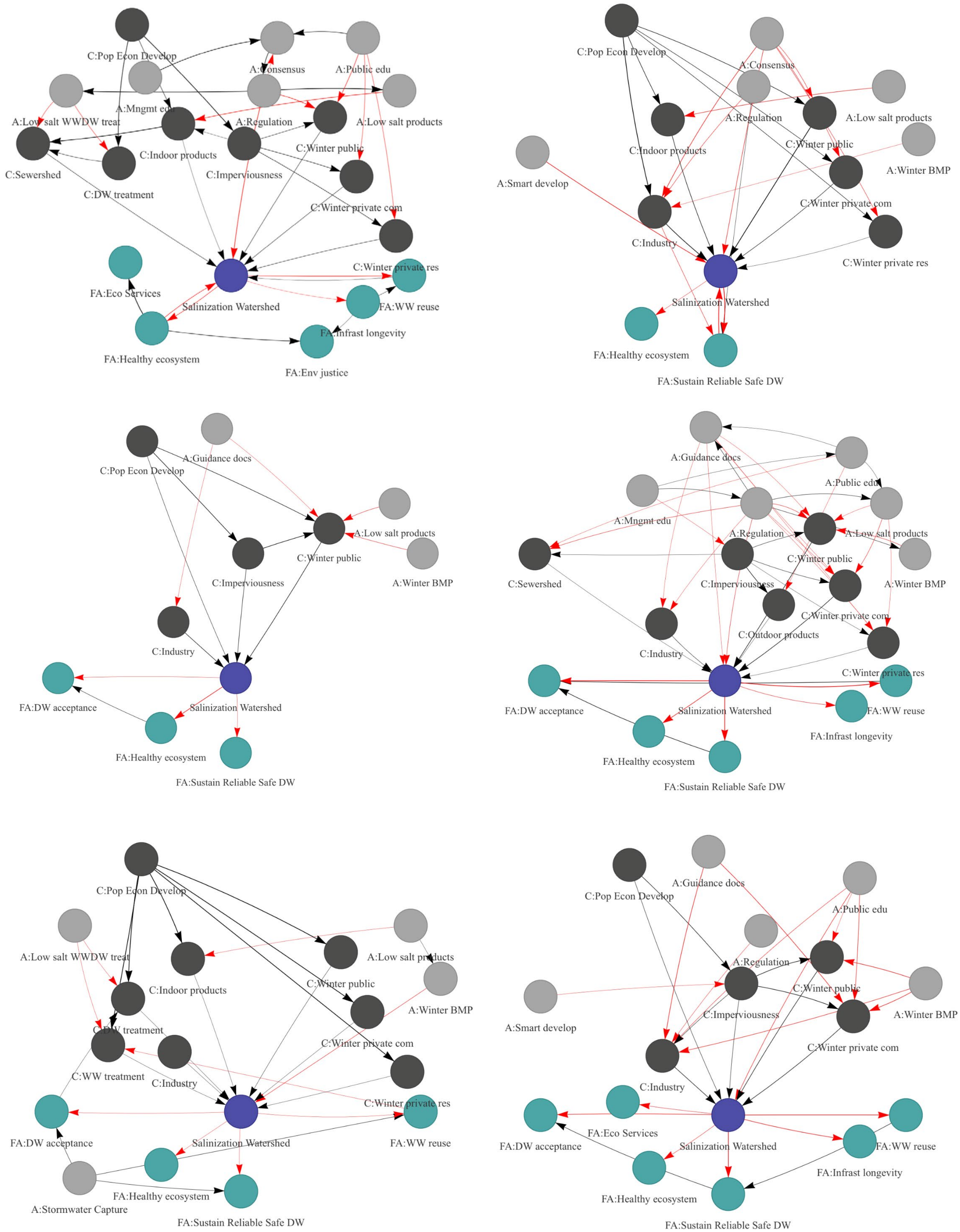
Supplemental Figure 5, Part 2



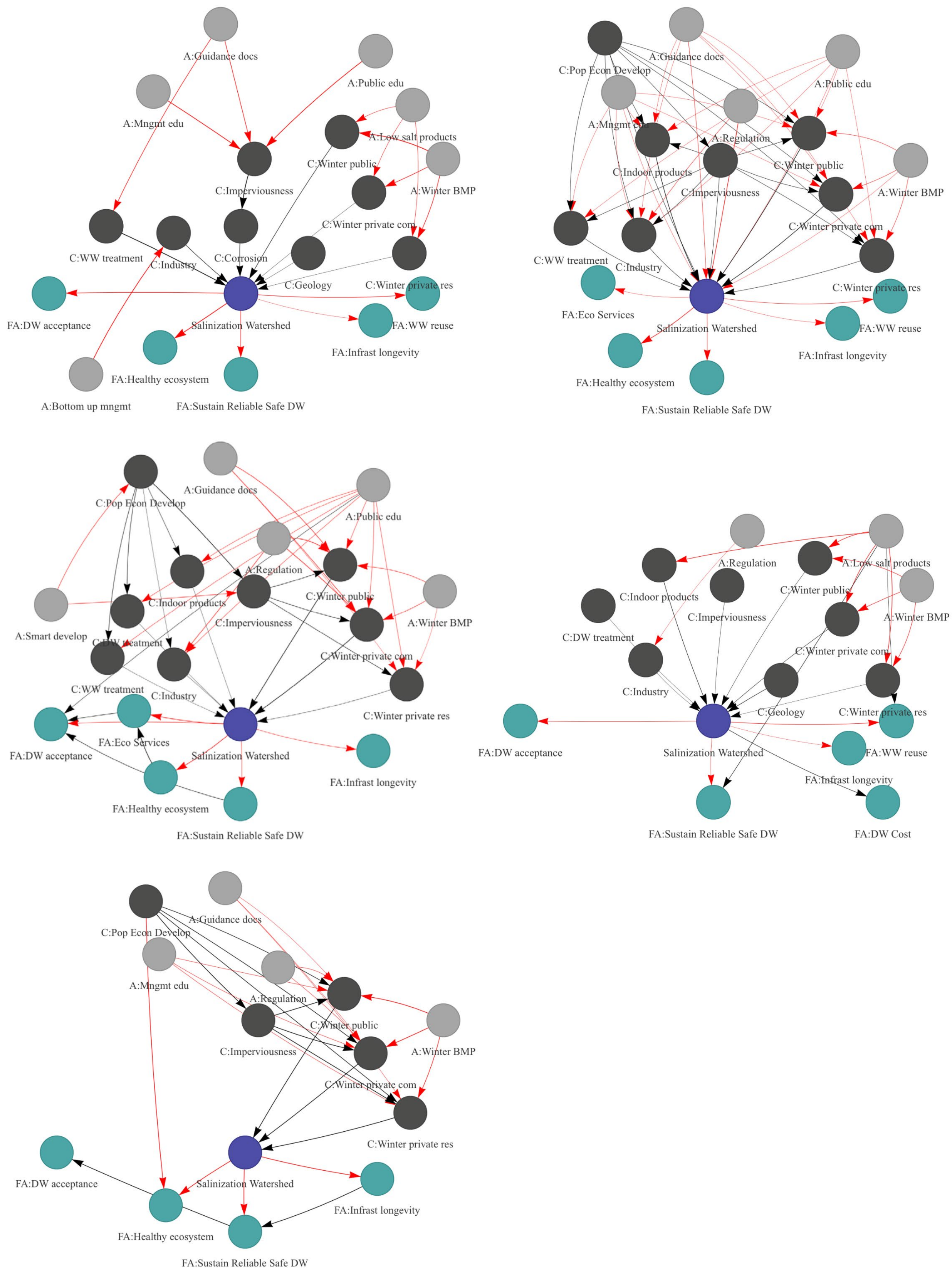
Supplemental Figure 5, Part 3



Supplemental Figure 5, Part 4



Supplemental Figure 5, Part 5



Supplemental Figure 5, Part 6

Supplemental Figure 5: Fuzzy Cognitive Maps (FCMs) representing the perceived SES for freshwater salinization for each individual stakeholder. Maps are shown in random order. The central concept (Salinization of the Watershed) is shown in blue, causes of salinization are shown in black, factors affected by salinization are shown in teal, and mitigating actions are shown in grey. See supplemental Tables 1-3 for full concept definitions. Black arrows indicate perceived causal relationships that are positive (i.e., concept 1 is presumed to increase concept 2) and red arrows indicate perceived causal relationships that are negative (i.e., concept 1 is presumed to decrease concept 2).

SUPPLEMENTAL METHODS

Dynamic Simulations

Dynamic simulations were conducted in R using the package fcm (Dikopopoulou & Papageorgiou, 2017). Concepts were associated with activation values using the following neural reasoning rule (Kosko, 1986):

$$A_i^{(t+1)} = f\left(A_i^{(t)} + \sum_{\substack{j=1 \\ i \neq j}} w_{ji} A_j^{(t)}\right) \quad [1]$$

where $A_i^{(t+1)}$ is the activation value of concept A_i at iteration $t+1$, $A_i^{(t)}$ is the activation value of concept A_i at iteration t, $A_j^{(t)}$ is the activation value of concept A_j at iteration t, and w_{ji} is the weight of the edge relationship between concept A_j and A_i in the weighted adjacency matrix. A hyperbolic tangent transfer function was used for $f(x)$:

$$f(x) = {(\exp(2\lambda x) - 1)}\Big/{(\exp(2\lambda x) + 1)} \quad [2]$$

where λ is a real positive number that determines the steepness of the transfer function and therefore the degree to which it squashes activation values at each iterative step (Aminpour et al., 2020; Knight et al., 2014; Koutsellis et al., 2022). The same value for λ was used for all dynamic simulations ($\lambda = 0.3$). Selection of this value was informed by Koutsellis et al., (2022). Briefly, the upper bound of λ that guarantees a unique simulation state was calculated for each aggregate FCM,

$$\lambda' = 1\Big/\sqrt{\sum_{i=1}^{n} \sum_{i=1}^{n} \left(w_{ij}^2\right)} \quad [3]$$

where λ' is the upper bound and n is the maximum number of model concepts. Starting with this bound (i.e., $\lambda = \lambda'$), we slowly increased λ, stopping at the largest value where a unique solution was still available across all aggregate FCMs, maximizing our ability to discern differences in final simulation outputs.

Because the hyperbolic tangent transfer function dampens activation values back to baseline (null) over multiple iterations of a simulation, we can evaluate the impact that perturbing any one concept (e.g., a salt source) has on another (e.g., Salinization of the Occoquan) by summing activation values for the response concept over the duration it remains perturbed. This approach was used to compare the perceived impact of various salt sources on freshwater salinization in this study, including bulk sewershed salt sources (in-home products, industry, water and wastewater treatment), bulk watershed salt sources (winter maintenance chemicals, local geology, agriculture, infrastructure corrosion), and the various sub-sources that comprise them.

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SUPPLEMENTAL DISCUSSION

Salt Management Strategy for Virginia (SaMS)

The Salt Management Strategy (SaMS) toolkit for Northern Virginia (ICPRB & VA DEQ, 2020) is a co-developed guidance document that integrates a variety of winter salt programs in the region. Examples include: (1) the Sustainable Winter Management (SWiM) program, which focuses on guidance, assessment services, training/certification and automated monitoring of salt application practices (WIT Advisers, 2022); (2) Winter Salt Watch, which engages citizens in monitoring and reporting salt spills (IWLA, 2022); (3) education and outreach programming for youth (e.g., the Winter Warriors comic book; Gralley, 2020) and the general public (e.g., salt smart social media messaging; Metropolitan Washington Council of Governments, 2022); and (4) specialized workgroups that address winter salts such as the Urban and Industrial Issues Workgroup and the Water Quality Workgroup (Potomac DWSPP, 2022a, 2022b). SaMS is the result of collaborative efforts by more than 55 stakeholders in the region, 17 of whom are participants in this study (ICPRB & VA DEQ, 2020).

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