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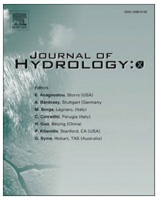

Simulating the emergence of institutions that reverse freshwater salinization: An agent-based modeling approach

Kingston Armstrong[a,*], Yinman Zhong[b], Shantanu V. Bhide[c], Stanley B. Grant[d], Thomas Birkland[b], Emily Zechman Berglund[a]

[a] Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, NC 27695, USA
[b] School of Public and International Affairs, North Carolina State University, Raleigh, NC 27695, USA
[c] Civil and Environmental Engineering, Virginia Tech, USA
[d] Civil Engineering, Virginia Tech, USA

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ABSTRACT

Salt concentration in global freshwater supplies has increased steadily, leading to the Freshwater Salinization Syndrome (FSS). To curb the FSS, stakeholders can self-organize to develop institutions, or a set of rules that limit salt emissions. This research develops an agent-based modeling framework to explore how institutions reverse the FSS. Property owners are represented as agents that apply rules of behavior to apply salt to deice pavement in response to winter weather, vote on institutions, and comply with or defect from institutions. Salt enters the soil-groundwater system through infiltration, which is modeled using a transit time distribution approach. Results demonstrate that stable institutions lead to positive economic outcomes for stakeholders, based on their ability to apply salt during winter events and access high-quality drinking water. Simulations are analyzed to explore institutions, or limits to the application of salt, that emerge based on the interactions of stakeholders as they agree on salt application limits, the intensity of monitoring for defectors, and sanctions. Institutions that emerge effectively limit the concentration of salt in drinking water. The emergence of stable institutions low rates of innovation among stakeholders, and the concentration of salt in groundwater exceeds standards due to high rates of defection among stakeholders. This research demonstrates how self-organized institutions can lead to sustainable application strategies that reverse the FSS.

1. Introduction

The freshwater salinization syndrome (FSS) is the trend of increasing levels of specific conductance, pH, alkalinity, and base cations along hydrologic flow paths from small watersheds to coastal waters (Kaushal et al., 2018). Waters are contaminated by anthropogenic salt inputs, such as road salts, salts used on private property, sewage, residential runoff, and irrigation runoff; accelerated weathering of natural geologic materials; and human uses of easily weathered material, such as concrete (Kaushal et al., 2005; Dugan et al., 2017; Kaushal et al., 2013). As a result, saline waters threaten aquatic life, accelerate deterioration of urban infrastructure, degrade drinking water supplies, and mobilize other aquatic contaminants (Kaushal et al., 2018; Novotny et al., 1998).

The degradation of the quality of water resources is predictable because freshwater is a common-pool resource (Schlueter and Pahl-Wostl, 2007; Nhim et al., 2019). Common-pool resources are available to multiple users, difficult to monitor and control, and subject to degradation through over-use (Ostrom, 2000). Water quality is a common-pool resource (Berke et al., 2013) because water bodies have a carrying capacity for a mix of pollutants and, similar to resource extraction, the amount of chemical or biological agents that can be discharged to the environment is limited. In the context of the FSS, individual property-owners, corporations, and municipalities apply salt to the surface of the landscape and discharge effluent that carries salt directly to water bodies that are needed for drinking water and ecosystem services. Similar to other common-pool resources, the FSS is characterized by 1) exludability: it is costly to prevent individuals from using a resource, and 2) subtractability: the use of the resource by one user prevents others from using that same resource (Grant et al., 2022). Resources such as freshwater quality were thought to pose a classic

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* Corresponding author.

E-mail addresses: kearmst4@ncsu.edu (K. Armstrong), yzhong22@ncsu.edu (Y. Zhong), bhidesv@vt.edu (S.V. Bhide), stanleyg@vt.edu (S.B. Grant), tabirkla@ncsu.edu (T. Birkland), emily_berglund@ncsu.edu (E.Z. Berglund).

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"tragedy of the commons", in which individuals extract goods or services from a shared resource in their own interests, and aggregated over-extraction depletes the resource (Hardin, 1968).

Not all common-pool resources are doomed to suffer the collapse predicted by the "tragedy of the commons" parable (Ostrom, 2000). Regulation treats a common as a centrally managed resource to create limits around access to the resource. Regulation can be expensive and inefficient because stakeholders have ready access to the resource and there is a high cost of monitoring and restricting access. Regulation may not take into account the knowledge and motivations of the community, neglecting important dynamics between stakeholders and decision-makers that drives sustainable extraction decisions. Institutions may emerge to manage the resource; these institutions embody a set of rules or norms that are adopted by stakeholders and control the degradation of the resource. Institutions can serve more efficiently than regulation in limiting damage to common-pool resources (Ostrom, 2010). While regulation is typically put in place as a reaction once the resource has experienced noticeable degradation in quality, institutions may emerge when degradation is detected or expected by a community of stakeholders who are interested in preserving the commons. Institutions mitigate exploitation through the dynamics of compliance, social norms, and sanctions. Stakeholders agree upon the quantity of resource that can be harvested by users. Once new rules are implemented, new patterns of compliance and sanctioning behaviors emerge dynamically, as individuals choose to comply, sanction non-compliance, and imitate other stakeholders (Ostrom, 1998; Aghaie et al., 2020). Compliance with institutions is typically driven by social norms, which are the expected behaviors, thoughts, values, or beliefs within a community (Castilla-Rho et al., 2017; Ostrom, 1998), in addition to social networks, and shared trust among peers (Herzog and Ingold, 2019; Schill et al., 2016). Compliance is important in common-pool resource settings because as more individuals comply with an institution, the resource does not deplete or lose quality as quickly (Rustagi et al., 2010; Gibson et al., 2005). However, resource sustainability can be jeopardized by a few resource users who defect from institutions (Gibson et al., 2005). Non-compliance can emerge due to outspoken and uniformed leaders (Schill et al., 2016), individualistic cultures (Castilla-Rho et al., 2019; Aghaie et al., 2020), and weak monitoring, resulting in the over-extraction of common pool resources (Ostrom, 1998; Ostrom and Walker, 2003). Compliance can be improved through sanctions, which are penalties applied for non-compliance (Castilla-Rho et al., 2019), the influence of peers through tightly connected social networks (Castilla-Rho et al., 2017), and increased monitoring of resource extraction. The cooperation of stakeholders through institutions can avert the need for what stakeholders may view as heavy-handed, top-down regulatory control of the resource (Ostrom, 2000). The emergence of institutions and social norms can improve resource longevity as more sustainable practices limit the exploitation of the resource.

The FSS is studied in this research as a common-pool resource problem using an agent-based modeling approach. Agent-based modeling simulates the interactions of autonomous agents within a shared environment (Holland, 1995) and can represent interactions and dynamic behaviors among stakeholders in a common pool resource system. An agent-based model includes a set of agents, specified by their attributes and behaviors; a set of agent relationships and methods for interaction; and an environment that is shared by agents (Macal and North, 2010). By simulating interactions among agents, agent-based modeling generates emergent outcomes that are not predictable as the sum of individual behaviors. Emergence is a system-level behavior, or new system state that appears due to feedback loops or network interactions among agents and between agents and the environment (Macal and North, 2010; Sawyer, 2005). Identifying patterns of emergence is critical in understanding complex adaptive systems because it indicates whether agents with randomly initialized behaviors are converging to stable patterns of behavior. Common-pool resource systems are distinctive in that institutions can emerge from the 'bottom up' to sustain the commons, and agent-based modeling readily provides tools and formulations to simulate interactions among stakeholders and the environment and generate emergent outcomes.

Agent-based modeling has been applied to a wide range of water resources systems to simulate a population of consumers or stakeholders as agents who use water resources, share information, and react to information and the level of service provided by the environment to update decisions and behaviors (Berglund, 2015). In the context of water quality, agent-based models were developed to represent water pollution discharge permitting systems (Zhang et al., 2013; Berglund, 2015); agricultural decisions and pollutant loads in water systems (Daloglu et al., 2014; Zekri et al., 2014; Ngo et al., 2021); and urban decisions to reduce phosphorous discharge to water systems Bitterman and Koliba (2020). Agent-based models have been developed to simulate theoretical, abstract common-pool resource systems (Schill et al., 2016; Sugiarto et al., 2017; Ghorbani et al., 2017; Ten Broeke et al., 2019; Kol'vekova et al., 2021; Andersson et al., 2021), fisheries (Klein et al., 2017; Henry et al., 2017), groundwater and surface water resources (Zekri et al., 2014; Nhim et al., 2019; Tamburino et al., 2020), forest resources (Bravo, 2010; Agrawal et al., 2013; Vallino, 2014), and electromagnetic spectrum bands for wireless transmission purposes (Bustamante et al., 2020). Studies in sociohydrology developed agent-based models to identify how social norms impact the use of water in a common-pool resource setting (Pouladi et al., 2020; Pouladi et al., 2019; Bakarji et al., 2017). Sociohydrological framework simulated conflicts and cooperation in the use of transboundary rivers for water supply Wei et al. (2022,). These applications found that diverse factors drive cooperative behaviors in contexts where the river serves as a common-pool resource. By simulating common-pool resources using an agent-based modeling approach, these studies test theories of individual action and group behavior and create new insight for managing resources through computer simulations (Deadman, 1999; Smajgl, 2007; Morano et al., 2018).

1.1. Research objective

The objective of this research is to explore the emergence of institutions that reverse salinization for freshwater systems. An agent-based modeling framework is developed to represent the socio-ecological system composed of human actors, or property owners, and their emission of salt to the soil–water-groundwater system. Simulations are analyzed to explore institutions, or limits to the application of salt, that emerge based on the interactions of stakeholders as they agree on salt application limits, the intensity of monitoring for defectors, and sanctions.

This research adopts an agent-based model, Self-OrgaNIzing the COMmons (SONICOM) (Ghorbani et al., 2017) to simulate the emergence of institutions in response to freshwater salinization. In SONICOM, agents use an energy function to select cooperative or defecting behaviors, vote on institutions, and are penalized for defecting. Agents represent private property owners across a landscape who apply salt to deice private parking lots and sidewalks in response to winter weather, such as ice and snow. Salt enters the groundwater through infiltration, modeled using a parsimonious model, premised on transit time distribution (TTD) theory, that accounts for the downward transport and mixing of salt through a transiently saturated vadose zone into groundwater. As concentration levels of salt in the groundwater increase, agents can adopt institutions, or limits on the rate of salt application. Agents are encoded with rules to represent behaviors, including applying salt, voting on institutions, and choosing to defect or comply with existing institutions. The agent-based model is applied for a hypothetical subcatchment to simulate changes in agent behaviors change to reverse the salinization of groundwater. The modeling framework simulates the emergence of institutions, including limits on resource use, monitoring, and penalties for non-compliance, to avert the tragedy of the commons in the context of freshwater salinization. Results are analyzed to explore the timing of cooperative decisions, the prevalence of defecting, and the effect of institutions on the concentration of salts in the vadose zone. The results of this study demonstrate the limitations that would emerge through stakeholder cooperation and the impacts of limits on salt concentration in water supply systems.

2. A typology of agent-based modeling formulations for simulating common pool resources

Agent-based modeling frameworks have been developed to simulate common pool resource systems using a range of concepts and mechanisms. Here we categorize existing frameworks within a systematic typology of agent-based modeling formulations (Fig. 1). First, the consumption of a common-pool resource within an agent-based model is depicted in Fig. 1a, where agents are encoded with basic behaviors, including observing the state of the resource, observing information about a sustainable harvest, deciding to cooperate or defect with the sustainable harvest, and extracting the resource. Without regulation or institutions, there is no feedback for agents to alter their extraction, and agent behaviors may lead to a tragedy of the commons.

Existing agent-based models for common pool resources include mechanisms to adjust harvesting behaviors through regulation (Fig. 1b). Models represent regulation as a centralized strategy to maximize social welfare across all agents, and agents follow prescribed limitations on extracting resources, without options for defecting (Schlueter and Pahl-Wostl, 2007; Brede and Boschetti, 2009; Zekri et al., 2014; Klein et al., 2017).

Existing agent-based modeling frameworks represent institutions as peer-to-peer informal sanctions (Fig. 1c), or formal sanctions applied through agreed-upon limits to resource extraction and monitoring (Fig. 1d). Agent-based models for both informal and formal institutions rely on the following set of core mechanisms.

1. **Agents receive information about the amount of resource that can be sustainably harvested.** The sustainable harvest may be predetermined and communicated by an exogenous agency (Bravo, 2010; Agrawal et al., 2013; Sugiarto et al., 2017; Nhim et al., 2019) or emergent as part of agent interactions (Schill et al., 2016; Vallino, 2014).
2. **Agents decide to cooperate or defect.** Defecting is the action of extracting an amount of resource greater than the sustainable harvest (Henry et al., 2017). Models use utility, payoff, or energy functions to select cooperation or defection and update the level of resource consumption accordingly. Decisions are based on terms including the state of the resource, the benefit of extraction, the benefit of following institutions, the benefit of cooperating, the cost of punishment for defecting, the cost of monitoring defectors, social preferences, and trust (Bravo, 2010; Agrawal et al., 2013; Vallino, 2014; Schill et al., 2016; Sugiarto et al., 2017; Ghorbani et al., 2017; Nhim et al., 2019; Bustamante et al., 2020; Kol'vekova et al., 2021; Ten Broeke et al., 2019).

Agents can apply decision rules to defect or cooperate that take into account social preferences (Schill et al., 2016), trust (Ten Broeke et al., 2019), and the state of the resource (Bravo, 2010), beyond the value of the payoff alone. Alternatively, Andersson et al. (2021) models opinion dynamics to represent the diffusion of opinions around cooperating and defecting, instead of using a rational utility-based decision-making model.

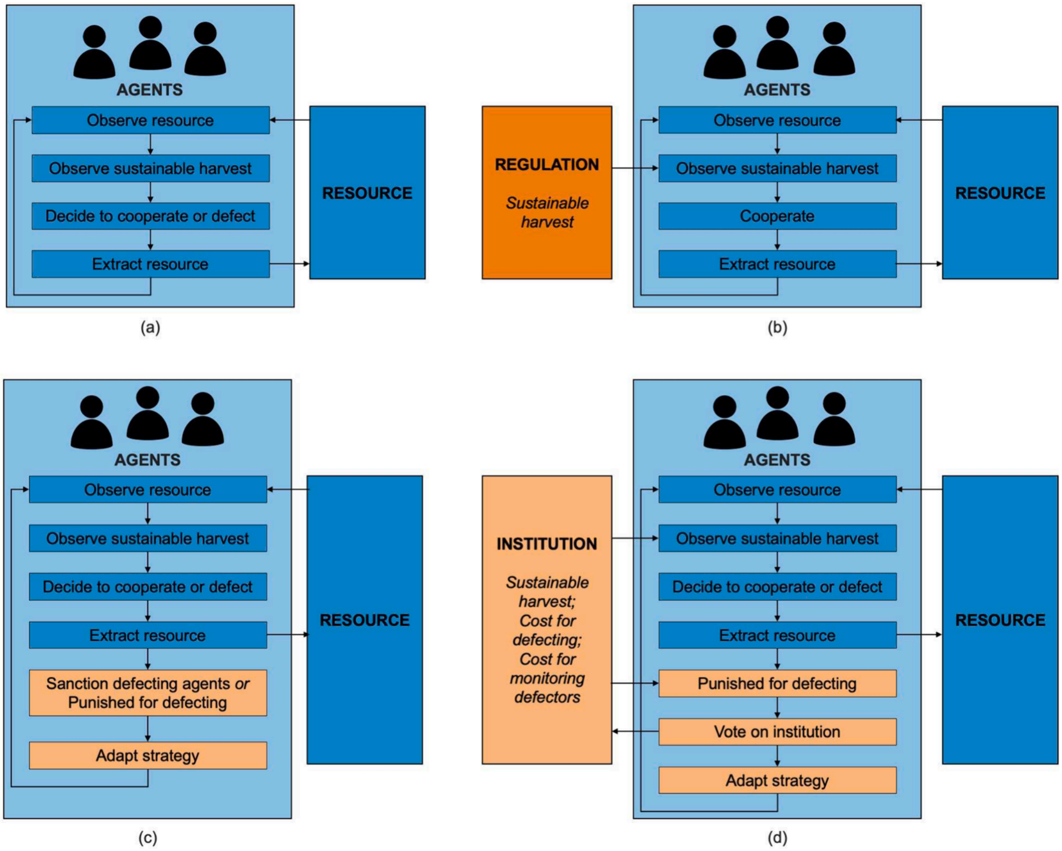

Fig. 1. Agent-based modeling simulates a common-pool resource and captures interactions between stakeholder agents and a resource system: (a) Agents that harvest from a common-pool resource without institutions or regulation may over-exploit a resource, leading to a tragedy of the commons; (b) Regulation defines a sustainable harvest for stakeholder agents; (c) Institutions can punish defectors through peer-to-peer sanctions and the use of interpersonal dynamics; (d) Institutions may emerge as agents vote on rules for resource extraction and punishment. This research applies SONICOM, which uses the formulation presented in (d).

3. **Defecting agents are punished.** The cost of punishment for defectors is modeled as a term that degrades the utility function (Ghorbani et al., 2017; Sugiarto et al., 2017; Nhim et al., 2019; Kol'vekova et al., 2021) or as the removal of the defector from the simulation, to represent that those stakeholders are no longer allowed access to the resource (Vallino, 2014). Punishment can also be represented as a loss of reputation, so that other agents are less likely to interact and cooperate with those agents in the future (Ten Broeke et al., 2019). Some models simulate peer-to-peer interactions between stakeholders to represent the use of interpersonal dynamics to punish defectors, such as ostracism (Sugiarto et al., 2017; Ten Broeke et al., 2019; Nhim et al., 2019). These applications use predetermined levels of sustainable harvest and apply punishment as a cost to defecting agents. A formal approach represents institutions as explicit limits for resource extraction and rules for punishment, and agents agree on the set of rules through voting (Bravo, 2010; Kol'vekova et al., 2021; Schill et al., 2016; Vallino, 2014; Ghorbani et al., 2017; Bustamante et al., 2020). These models use explicit rules to represent that when agents become dissatisfied, they vote on an institution to specify the allowable level of resource extraction, the frequency of monitoring for defectors, and the fines that are levied for defectors. Some models do not include an explicit punishment mechanism beyond the eventual degradation of the resource (Bravo, 2010; Agrawal et al., 2013; Andersson et al., 2021; Schill et al., 2016). All agents in the community pay a cost for punishment, as monitoring and enforcing penalties associated with violations requires time and resources paid by enforcing stakeholders (Ghorbani et al., 2017; Sugiarto et al., 2017; Nhim et al., 2019; Kol'vekova et al., 2021).
4. **Agents adapt their strategy for harvesting.** Many models simulate that the agents attempt to withdraw a desired extraction from the commons, and when the resource is over-extracted, agents experience unmet demands, leading to dissatisfaction. Agents can observe the state of the resource and use this information to select to cooperate or defect in the next timestep, based on beliefs of what the state of the resource should be (Bravo, 2010). Agents copy strategies of other agents, innovate a new strategy, and vote on institutions (Vallino, 2014; Schill et al., 2016; Ghorbani et al., 2017; Sugiarto et al., 2017; Ten Broeke et al., 2019; Nhim et al., 2019; Kol'vekova et al., 2021).

3. Agent-based modeling framework

In this research, we adopt an approach that simulates the emergence of institutions through voting, representing that stakeholders self-organize in a formalized setting to find a shared set of rules, rather than adopt limitations based on peer-to-peer interactions alone (as shown in Fig. 1d). This model was selected based on on-going research of the FSS that uses stakeholder meetings to facilitate conversation around salt standards for freshwater and the anthropogenic causes of salinization (Grant et al., 2022). SONICOM (Ghorbani et al., 2017) simulates the emergence of institutions by representing agents that use an energy function to select cooperative or defecting behaviors, vote on institutions, and punish defecting agents. This is the first research study that applies SONICOM to simulate the emergence of institutions for the FSS.

This research couples SONICOM and TTD modeling to simulate property-owners who apply salt and the fate and transport of salt in a soil–water-groundwater system (Fig. 2). Property-owners are represented as agents that apply salt for deicing paved surfaces, observe salt concentration in the vadose zone, which represents groundwater as a drinking water resource, and select an institution through voting. The TTD model simulates the transport and fate of salt in the vadose zone and is coupled with the agent-based model. The case study application that is used in this research is a hypothetical land parcel representing an office park of businesses in Virginia. This case study was created to study the FSS and contribute to on-going research around salinization of the Occoquan Reservoir in northern Virginia.

The agent-based model formulation is described using the Overview Design Details (ODD) protocol as follows (Grimm et al., 2006). For brevity of presentation, Design Concepts, which are part of the Details section, are presented in the Supplemental Material.

3.1. Overview

3.1.1. Purpose

The purpose of the agent-based model described here is to study the emergence and evolution of institutions in the context of freshwater salinization.

3.1.2. State variables and scales

The model includes a set of agents representing property-owners and a shared vadose zone and groundwater system. An institution is selected by property-owners and is represented by a set of rules.

An agent is assigned a lot area and pavement area that should be deiced after winter events. Agents are also assigned economic benefits associated with de-icing and costs associated with salinized drinking water. Agents are not assigned spatial locations within a watershed; the impacts of salt-contaminated infiltration are calculated as an average across agents (as described in Section 3.1.5). At initialization, agents are connected to 2–10 agents that make up their social network. The social network represents friends, acquaintances, or colleagues who

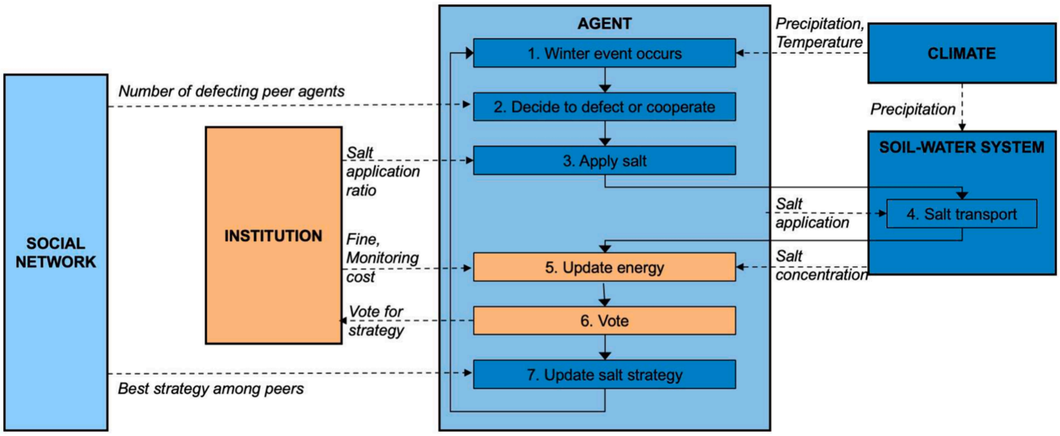

Fig. 2. Agent-based modeling framework couples modules that represent property-owner agents, a social network, an institution, climate, and soil–water system. Parameters that are passed between modules are shown in italics. The steps described in the process overview are labeled numerically.

communicate deicer strategies and their economic performance. An agent has knowledge about the decision to defect and salt application willingness of each peer agent in its social network.

The parameters and state variables that are used in the agent-based model are shown in Tables 1 and 2, respectively. Parameters that describe the geographic and environmental variables were created to represent a realistic area (Tables 1). Preliminary analysis was used to adjust variables to test for reasonable dynamics, including the concentration of salt in groundwater and the balance between the cost of treating salinized water and the economic benefit of de-icing parking lots. Parameters that are difficult to quantify, such as beliefs around monitoring intensity and fines, were randomly initialized for each agent. Parameters that represent innovation and defection were tested through sensitivity analysis in Section 4.4.

The model operates on daily time steps. On days with cold weather precipitation events, agents decide how much salt to apply. Salt application strategies (hereafter referred to as strategies) consist of a set of values, representing the salt application willingness ($S_i(t)$), fine belief (F_i), and monitoring intensity belief (MI_i). Salt application willingness is the fraction of the required salt application rate that the agent uses to apply salt. The salt application willingness is initiated from a finite set of options, in the range of 0.0–1.0 (in increments of 0.05). The fine belief represents the amount an agent thinks a defector should be fined, and the monitoring intensity belief represents how many people in the population are checked for defecting. Fines and monitoring bear costs to both defecting and cooperating agents, as cooperating agents conduct or administrate monitoring. Agents make decisions based on their energy, which represents economic gains and losses associated with salt application and salt concentration in drinking water sourced from the local groundwater (which is connected to deicing practices through the vadose zone TTD model presented later).

3.1.3. Process overview and scheduling

The overview of daily steps is provided here. Detailed descriptions and mathematical formulations are provided in Section 3.1.5.

Step 1. Agents receive climate information. Agents observe daily precipitation, pavement temperature, and the occurrence of a winter event.

Step 2. Agents decide to defect or cooperate. Agents select defecting or cooperating with an institution based on a prediction of which action would result in a higher energy gain.

Step 3. Agents apply salt. Agents that defect use their strategy to apply salt if a winter event occurred that day. The agent's strategy is based on the paved area, the precipitation event, the pavement temperature, and the salt willingness. If the agent cooperates with the institution, it applies the rate that is specified by the institution.

Table 1
Parameters for agents. Subscript i refers to i^{th} agent. * denotes parameter values that are tested through sensitivity analysis.

Model Component	Parameter	Description	Setting for case study
Model	N	Number of agents	100
Model	TT	Salinity Taste Threshold	$[Cl^{-}] = 30g/m^3$
Agent	F_i	Fine belief	U(0,1)
Agent	MI_i	Monitoring intensity belief	U(0,1)
Agent	MC	Monitoring fee	U(0,10)
Agent	IR_i	Likelihood to innovate instead of copy peers	0.5*
Agent	SI_i	Likelihood to follow neighbors' actions	0.85
Agent	DP_i	Likelihood to defect	0.15*
Agent	α_1	Relative benefit of deicing	$0.01/10g/m^2$
Agent	α_2	Relative cost of salinized water	1
Agent	L	Number of peer agents in a network	2–10
Agent	PA_i	Permeable area of property	30 m^2
Agent	IA_i	Impervious area where salt is applied	2000 m^2
Institution	ITE	Institutional emergence time	60 days
Institution	th_{inst}	Threshold for institutional change	0.15
Institution	θ_R	Percent of agents refunded	0.25

Table 2
State variables for agents, institution, and environment. Subscript i refers to i^{th} agent; t refers to timestep.

Model Component	State Variable	Description	Calculation or Source
Environment	$T(t)$	Pavement temperature	Input data
Environment	$P(t)$	Precipitation depth	Input data
Environment	$W(t)$	Winter event occurred	Step 1
Environment	$C(t)$	Salt concentration in vadose zone discharge	Step 4
Agent	$D_i(t)$	Decision to defect	Step 2
Agent	$M_i(t)$	Salt application rate	Step 3
Agent	$E_i(t)$	Energy	Step 5
Agent	$S_i(t)$	Salt application willingness	Step 7
Institution	$I(t)$	Allowable salt application ratio	Step 6
Institution	$F(t)$	Fine	Step 6
Institution	$M(t)$	Monitoring intensity	Step 6

Step 4. Salt is transported through the vadose zone to shallow groundwater. Salt is transported through the vadose zone to shallow groundwater. A TTD model is used to simulate the transport and mixing of salt in the vadose zone. Salt application rates of all agents ($M_i(t)$ for all i) at each time step are used as input to the TTD model to simulate the concentration of salt in groundwater ($C(t)$).The model is described in detail in the Supplemental Material.

Step 5. Agents update energy. Agents gain energy each day to represent economic activity associated with salt application decisions. On days when there is a winter event, agents gain energy in proportion to the amount of salt that is applied, representing the reduction in monetary gains that property-owners receive if they do not deice every stall, or parking space, in a parking lot. Agents lose energy when the concentration of salt in the vadose zone exceeds a salt threshold.

When an institution is established, agents pay monitoring fees, which are used to collect fines from defecting agents. Agents receive an incentive when they comply, which is a gain in energy.

Step 6. Agents vote on an institution. A vote is held in an interval equal to the institutional emergence time, or when the number of agents in the population with negative energy exceeds a threshold. To vote, agents submit their current strategy (which includes values for the salt application willingness, fine belief, and monitoring intensity belief) as their vote. The mode of the votes is selected as the institution, which specifies the allowable salt application ratio, the fine for defecting, and the monitoring intensity.

Step 7. Agents update salt application strategies. An agent makes a decision to continue with its current strategy or to find a new strategy. If an agent's current energy level is negative, the agent updates its strategy by innovating or copying its most successful neighbors. An agent that innovates selects new randomized values for salt application belief, fine belief, and monitoring intensity belief. Otherwise, the agent selects the strategy of the agent with the highest energy in its network.

3.1.4. Initialization, input, and implementation

The model is developed for a hypothetical land parcel representing an office park where 100 businesses are grouped together. Agents are initialized to represent 100 property-owners who decide to apply salt in response to cold weather events. Agent characteristics that are needed as input are listed as parameters in Table 1. All agents are initialized with salt application willingness set at 1.0 to represent stakeholders who are not initially aware of salinizing water.

Input that are required to initialize the model include a time series of temperature, precipitation, and evapotranspiration data. This research used data to reflect a climate in Virginia, USA. Snowfall and evapotranspiration data were collected at the National Oceanic and Atmospheric Administration (NOAA) Station#USW00093738, which is located at the Washington Dulles International Airport, from December 2000 until December 2013. A 21-year period was created by repeating the first eight years of the 13-year dataset. Meteorological data and vegetation data were used to determine expected evapotranspiration and infiltration rates.

From the daily precipitation and temperature data, the TTD model calculates a daily time series of salt concentration discharged from the vadose zone to groundwater (described below). In this framework, the taste threshold for salt is used at 30 $\frac{g}{m^3}$ (U.S. EPA, 2003). The TTD model is implemented in Mathematica, and the agent-based model is implemented in NetLogo. The models were run on a Intel Core i7-12700F (2.1 GHz). The TTD model requires approximately 48 h to run. The TTD model is executed once for the climate data, and one set of hydrologic flows are used as input for the agent-based model. The agent-based model requires 40 s to run one simulation. The agent-based model was run in parallel across multiple cores, which reduced the wall clock time to 21 s per simulation.

3.1.5. Submodels

Agents receive climate information. Agents observe daily precipitation ($P(t)$) and pavement temperature ($T(t)$). If precipitation is greater than or equal to a precipitation threshold (e.g., 0.1 cm) and temperature is less than or equal to a temperature threshold (e.g., 32°F), then a winter event occurred ($W(t) = 1$). Otherwise, a winter event did not occur ($W(t) = 0$).

Agents decide to defect or cooperate. Once an institution is in place, an agent can comply with the institution or defect, in which the agent applies its individual strategy, or salt application willingness. First, an agent evaluates if the gain in energy from following its individual strategy would be higher than following the institution. If the institution leads to lower energy, the agent chooses to defect using Eqn. 1.

$$D_i(t) = \begin{cases} 0, & \text{if} r < DP_i \times (1 - SI_i) + \dfrac{\sum\limits_{j=1}^{N_i} D_j(t-1)}{N_i} \times SI_i \\ 1, & otherwise \end{cases} \tag{1}$$

where r is a random real number between zero and one; and N_i is the number of agents in agent i's network. $D_i(t)$ is the decision of agent i to defect at time step t and represents the decision as a binary variable (0 = does not defect; 1 = defects). Defecting propensity is the probability of defecting, specified for each agent as DP_i, and social influence, SI_i, represents how the decisions of other agents are weighted by the agent to determine to defect. To determine the number of defectors that influence an agent, agents check whether an agent they are connected to has defected since the last voting cycle and sums the number of defecting agents to determine the proportion of defecting neighbors: $\frac{\sum_{j=1}^{N_i} D_j(t-1)}{N_i}$.

Agents apply salt. If no institution has been initiated, then agents use the following equation to apply salt.

$$M_i(t) = \begin{cases} R(t) \times S_i(t), & \text{if} W(t) = 1 \\ 0, & \text{if} W(t) = 0 \end{cases} \tag{2}$$

where $M_i(t)$ is the amount of salt that is applied to paved areas by agent i at timestep t. The salt application is calculated based on the agent's salt application willingness ($S_i(t)$) and the required salt application rate associated with the precipitation event ($R(t)$). The required salt application rate ($R(t)$) is determined based on precipitation and pavement temperature, as shown in Table 3.

If, on the other hand, an institution has been established, then agents apply salt in response to a winter precipitation event based on the agent's decision to defect, as follows.

Table 3
Required salt application rate is determined using pavement temperature and precipitation.

Snow depth (cm)	Pavement temperature (°C)	Salt application rate (g/m^2)
⩾0.1	$-2 < T(t) \leq 0$	$M_i(t) = 11$
	$-5 < T(t) \leqslant -2$	$11 \leqslant M_i(t) \leq 22$
	$-9 \leqslant T(t) \leqslant -5$	$11 \leqslant M_i(t) \leq 34$

$$M_i(t) = \begin{cases} R(t) \times S_i(t), & \text{if } W(t) = 1 \& D_i(t) = 1 \\ R(t) \times I(t), & \text{if } W(t) = 1 \& D_i(t) = 0 \\ 0, & \text{if} W(t) = 0 \end{cases} \tag{3}$$

where $I(t)$ is the allowable salt application ratio that is specified by the institution.

Agents update energy. Agents gain energy at each time step, or day, to represent economic activity associated with salt application decisions. On days when there is a winter event, agents gain energy in proportion to the amount of salt that is applied. This represents the reduction in monetary gains that property-owners receive if they do not deice every stall, or parking space, in a parking lot.

$$\Delta E_{E,i}(t) = \alpha_1 \times \frac{M_i(t)}{R(t)}, \text{if} W(t) = 1 \tag{4}$$

where $\Delta E_{E,i}(t)$ is the gain in energy due to economic activity, and α_1 is a coefficient.

Agents lose energy when the concentration of salt in the vadose zone ($C(t)$) exceeds a salt threshold (th_{salt}).

$$\Delta E_{S,i}(t) = \begin{cases} \alpha_2, & \text{if} C(t) \geqslant th_{salt} \\ 0, & \text{if} C(t) < th_{salt} \end{cases} \tag{5}$$

where $\Delta E_{S,i}(t)$ is the change in energy due to the salt concentration in the vadose zone, and α_2 is a coefficient.

Finally, when an institution has been established, agents can gain energy through using low application rates to represent that agents are provided an incentive to act sustainably. When an institution has been established, agents pay monitoring fees, which are used to collect fines from defecting agents. The incentivization pool is based on monitoring fees and is distributed to the top performing agents, or a fraction (denoted as θ_R) of agents with the lowest salt application strategy.

$$\Delta E_{I,i}(t) = \begin{cases} \dfrac{\alpha_3 \times M(t) \times N}{\theta_R \times N}, & \text{if agent } i \text{ receives incentive} \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

where $\Delta E_{I,i}(t)$ is the change in energy due to the incentivization; α_3 is a coefficient; $M(t)$ is the monitoring fee per agent; N is the number of agents; and θ_R is the fraction of agents that receive the incentive.

The energy at the current time step is updated at each time step using Eqn. 7.

$$E(t) = E(t-1) + \Delta E_{E,i}(t) - \Delta E_{S,i}(t) + \Delta E_{I,i}(t) \tag{7}$$

The parameters α_1 and α_2 represent the relative benefit of deicing and cost of treating a salinized water source on the economic outcome for agents.

Agents vote on an institution. At each voting time step, agents vote on an institution. The collective decision to change or initiate an institution occurs after a number of time steps equal to the institutional emergence time (*IET*). An institution can also be selected through a new vote when the threshold for institutional change (th_{inst}) is met. The threshold for institutional change is calculated as the ratio of agents in the population with negative energy to the agents in the population with positive energy. Once the number of agents with negative energy, representing dissatisfaction with their economic gains, increases, the agents vote on a new institution.

To vote, agents submit their own current strategy (which includes the salt application willingness ($S_i(t)$), fine belief (F_i), and monitoring intensity belief (MI_i)) as their vote. The mode of the votes, or the most frequent individual strategy, is selected as the institution, which specifies the allowable salt application ratio ($I(t)$), the fine for defecting ($F(t)$), and the monitoring intensity ($MI(t)$).

Agents update salt application strategies. An agent makes a decision to continue with its current strategy or to find a new strategy at every time step based on the energy level. If an agent's current energy level is negative, an agent updates its strategy by innovating or copying its most successful neighbors. Each agent is assigned an innovation rate, IR_i, and if $r \leqslant IR_i$, where r is a random number, then the agent chooses a new strategy by randomly selecting values for each of the strategy variables, including salt application belief, fine belief, and monitoring intensity belief. Otherwise, the agent selects the strategy of the agent with the highest energy in its network.

4. Results

4.1. Modeling scenarios

The agent-based modeling framework was applied for two base case modeling scenarios, including 100 simulations without institutions and 100 simulations with institutions. For the base case, the likelihood to innovate (IR_i) is set at 0.5, and the likelihood to defect (DP_i) is set to 0.15. Sensitivity analysis is conducted to test the effects of defecting and innovation on model outcomes, with institutions active. A total of 441 modeling sensitivity scenarios are executed for 100 random realizations each (44100 simulations).

4.2. Base case simulation

The base case modeling scenario was executed for one simulation to generate Fig. 3, which demonstrates the snow events that occurred within the first 1400 days of the simulation. Agents apply deicer following each snow event. The vadose zone salt concentration initially increases in response and gradually decreased as salt exited the vadose zone. Periods with multiple consecutive snow days demonstrate longer periods with sustained high salt concentration and higher increases in vadose zone concentration. In contrast, periods with fewer consecutive snow days show faster decay of vadose salt concentration.

Results for one simulation over the 21-year period are shown in Fig. 4. The salt concentration in the vadose zone exceeds the taste threshold after 113 days (Fig. 4a). Agents vote on an institution application rate by submitting their values for willingness, and the mode of the votes is applied as the institution rate (Fig. 4c). Agents lose energy during the periods when the salt concentration exceeds the threshold (Fig. 4b), and agents reduce their values for salt application willingness (Fig. 4d). The institution application rate is similar to the agent willingness; however, the institution rate drops to zero toward the end of the simulation (Fig. 4c). The discrepancy between the average of the willingness and institution rate is due to the presence of defectors that applied their willingness as the application rate instead of applying the institution rate. Defection leads to higher application rates and a salt concentration that crossed the taste threshold. As a result, lower energy states lead to lower values for willingness and, eventually, a lower institution application rate.

4.3. Effects of institutions in reversing salinization

The effect of institutions on salinization is explored through base case simulations. The base case was executed for 100 simulations with institutions active, as described above, and for 100 simulations *without* institutions. For the base case without institutions, the concentration exceeds the taste threshold early in the simulation (Fig. 5a). As a result, agents lose energy (Fig. 5b), and agents respond through innovation, where they create a new random willingness or copy the willingness of the agent with the highest energy in their network. Because the institution is not included in the model, agents only increase energy through applying deicer to gain economic benefits. As a result, the salt concentration gradually increases throughout the 8500 day simulation period and remains above the salt taste threshold after approximately 6000 simulated days onward (Fig. 5a). This prolonged period above the taste threshold leads to a consistent downward trend in both the average of

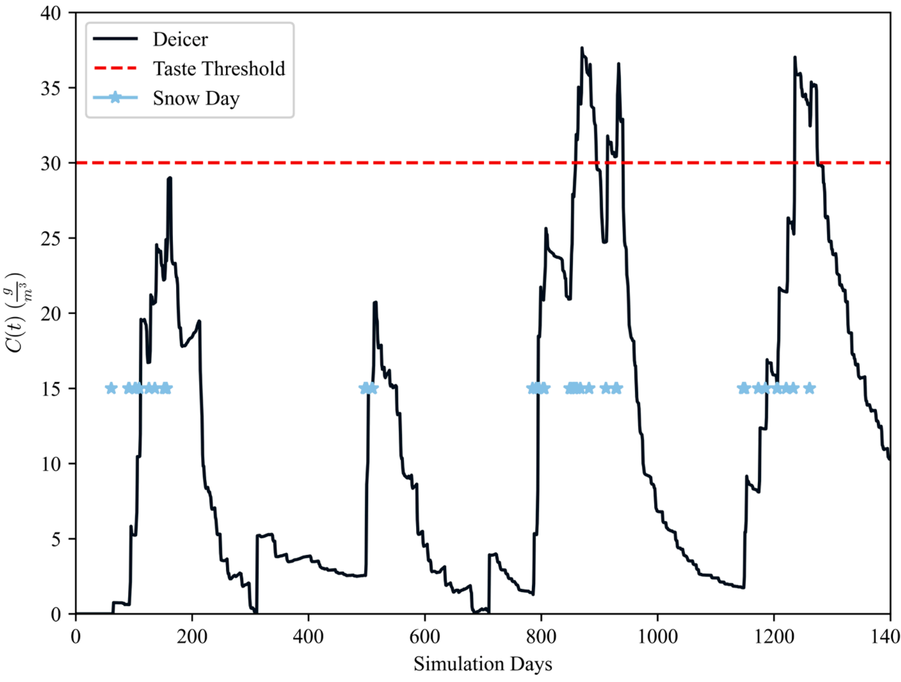

Fig. 3. Deicer concentration in the vadose zone, shown for the first 1400 days of the base case simulation.

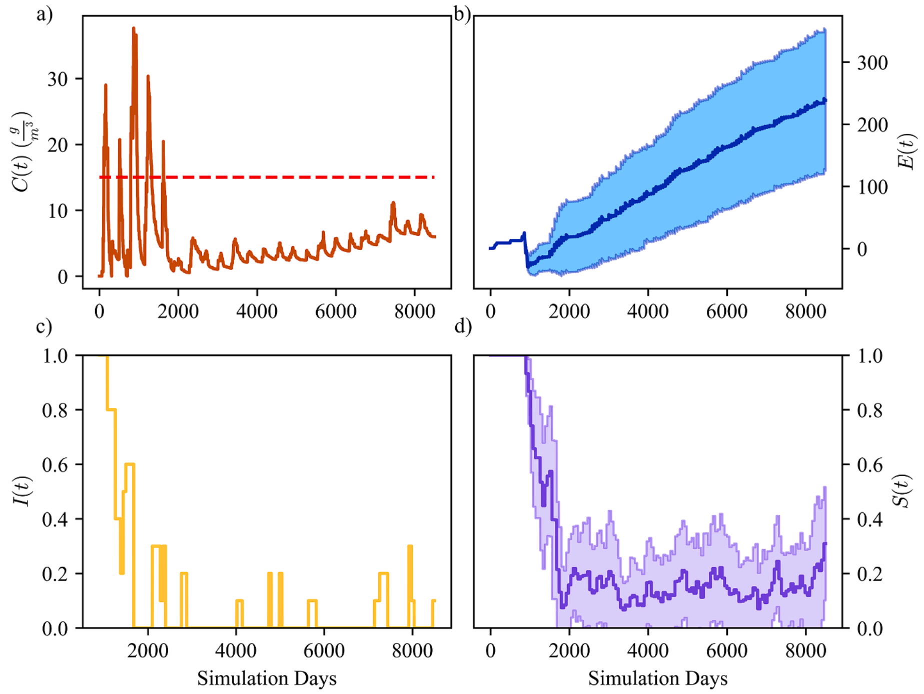

Fig. 4. Base case scenario results are reported for one simulation (a) vadose zone deicer concentration, (b) average energy of all agents, (c) institution deicer application strategy, and (d) average willingness of all agents.

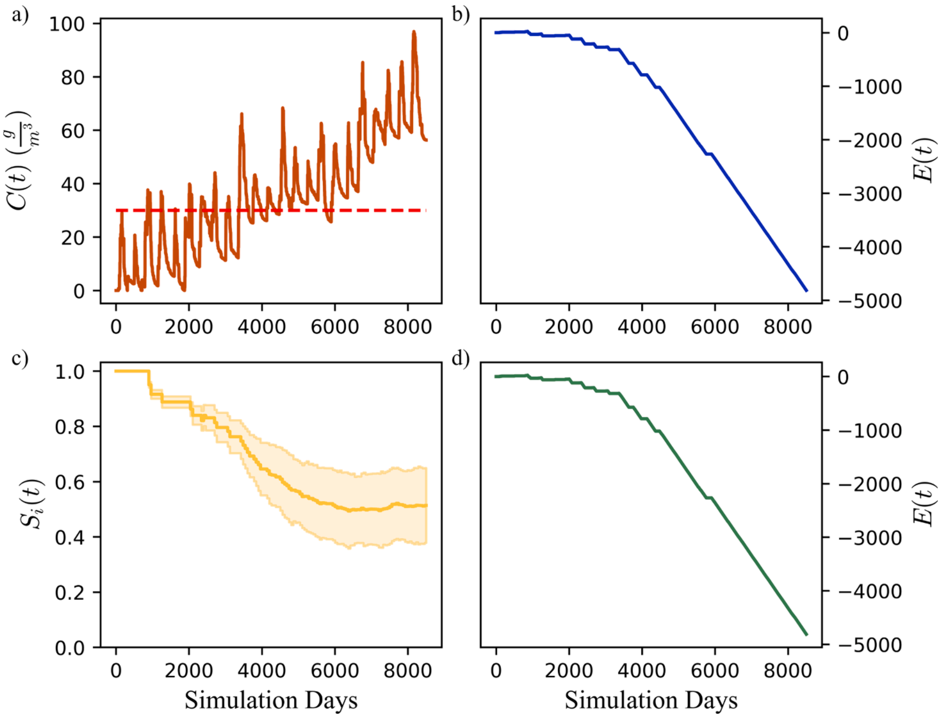

Fig. 5. Base case scenario was run without institutions for 100 simulations to report (a) the average vadose zone deicer concentration, (b) the average energy, (c) the average salt application willingness, and (d) the mode of the energy. Bands are shown as the standard deviation for each series.

the agent energy and the mode of the agent energy (Figs. 5b and d). Agents randomly adjust their application strategies to improve their energy, and the average willingness across the agents stabilizes around 0.5 (Fig. 5c). Application rates vary in the range of 0.0–1.0 and are adjusted by 0.2 at each time step. The convergence to 0.5 does not represent a viable application strategy to maintain a sustainable system, but an average rate that emerges from randomized changes. Across the 100 simulations, there is little variation reported in the water quality outcomes (Fig. 5a); that is, the time series of the salt concentration varies negligibly among simulations, and the small bands surrounding the time series represent the standard deviation of deicer concentration at each time step (Fig. 5a). In contrast, agent willingness us highly variable as indicated by the wide bands (Fig. 5c). Higher variability in agent behaviors is a result of the mechanisms for updating willingness based on innovation, which is activated when agents lose energy. After the time step when the salt threshold is exceeded, agents lose energy at every time step and change their strategy every 60 days. Although there is significant variation in agent behaviors, a consistent trend of increased salinity beyond the taste threshold is reported for each of the 100 simulations.

The base case modeling scenario is executed for 100 simulations with mechanisms that activate institutions. For many simulations, the vadose zone salt concentration crosses the taste threshold early in the simulation, and institutions emerge to keep the concentration below 30 $\frac{g}{m^3}$ (Fig. 6a). The composite average energy of all agents is reported as the average energy of 100 agents at each time step and across 100 simulations. The average energy declines throughout the simulations (Fig. 6d). Energy losses also derive from agents who select to defect. Defectors typically apply higher deicer application rates that contribute to high concentration in the vadose zone, and, subsequently, lower states of energy (Fig. 6d). Throughout all simulations, there us an average of approximately 10 agents that defect at each time step (Fig. 6g). Fig. 6e demonstrates that the salt application willingness declines significantly for all simulations, and, similarly, the institution application rate declines (Fig. 6f). Agents that vote on an institution not only vote for the institution application rate, but also the monitoring intensity (Fig. 6b), and the fine for defecting (Fig. 6c). The fine remains nearly static at 0.5 energy units throughout the simulations. However, the monitoring intensity gradually decreases from 50% to 25% during the simulations due to the associated monitoring costs. As a result, fewer defectors are caught and fined, as shown in Fig. 6h, despite the number of defectors remaining constant, as depicted in Fig. 6g. The ability of the institution to detect defectors impacts the final energy state of each simulation. The distribution of the average energy at the final time step of the 100 simulations is shown in Fig. A.1. The distribution is left skewed because most agents are able to recover initial energy losses, and agents that defect frequently report the lowest values for final energy states.

Comparing simulations with and without institutions demonstrates that the emergence of institutions, which is facilitated by voting and monitoring ameliorates salinization of the vadose zone. Before the vadose zone salt concentration exceeded the taste threshold, the concentration profiles were identical for the cases with and without institutions. After the threshold was crossed, salt concentrations for the two scenarios diverged, because institutions were not active to incentivize sustainable application strategies. Without institutions, agents gained energy from applying deicer and could not recover energy losses without further contributing to salinizing the vadose zone. In contrast, the emergence of a sustainable institution stabilized the salt concentration. Emergence of a sustainable salt application strategy occurred after 1743 days (Fig. 6) and fluctuated at around 0.1 for the remainder of the simulation.

4.4. *Exploring emergence of institutions: sensitivity analysis to innovation and defection*

The emergence of institutions is explored by evaluating the emergent institution salt application rate and concentration of salt in the vadose zone. A sensitivity analysis is conducted to execute simulations that varied likelihood to innovate (IR_i) and likelihood to defect (DP_i) from 0–1.0 in increments of 0.05 (441 combinations). Each setting is simulated for 100 random realizations to capture the effects of stochasticity.

The institution application rate emerges based on agent interactions, and the average value at the final time step across 100 simulations is shown in Fig. 7. The institution salt application is somewhat robust across the scenarios, with average values ranging between 0.11 and 0.20 for innovation rates ranging from 0.25 to 0.90. The rate of defection does not affect the emergent value of the institution. As the innovation rates increase from 0.05 to 0.20, institution application rates drop from high values of 0.60 to 0.22. At lower innovation rates, agents copy their neighboring agents' strategies, rather than randomly selecting a new value for the rate of application. The population is initialized with willingness set at 1.0, and with low rates of innovation, high values are used to vote and are copied by other agents. This mechanism is also reflected in the standard deviation of institution values (Fig. 8), which shows that at lower innovation rates, there is more variation in the institution across the 100 simulations. Lower innovation leads to less predictability in the final value of the institution application rate, as the institution rate is not able to converge to a stable value. Innovation rates that exceed 0.20 provide enough new strategies in the population to allow the institution to vary and reach lower values. At very high rates of innovation, the institution application rate is slightly higher, around values of 0.30. High rates of innovation indicate that agents frequently

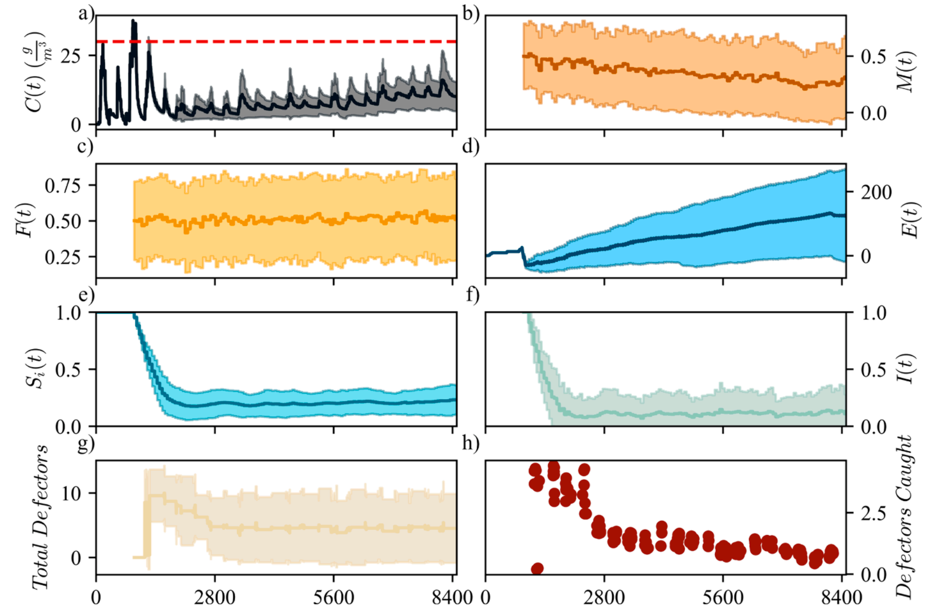

Fig. 6. Base case scenario was run with institutions for 100 simulations to report (a) average vadose zone salt concentration, (b) average monitoring intensity, (c) average fine for defecting, (d) average energy, (e) average salt application willingness, (f) average institution application rate, (g) average number of agents defecting, and (h) average number of defectors caught. Bands are shown as the standard deviation for each series.

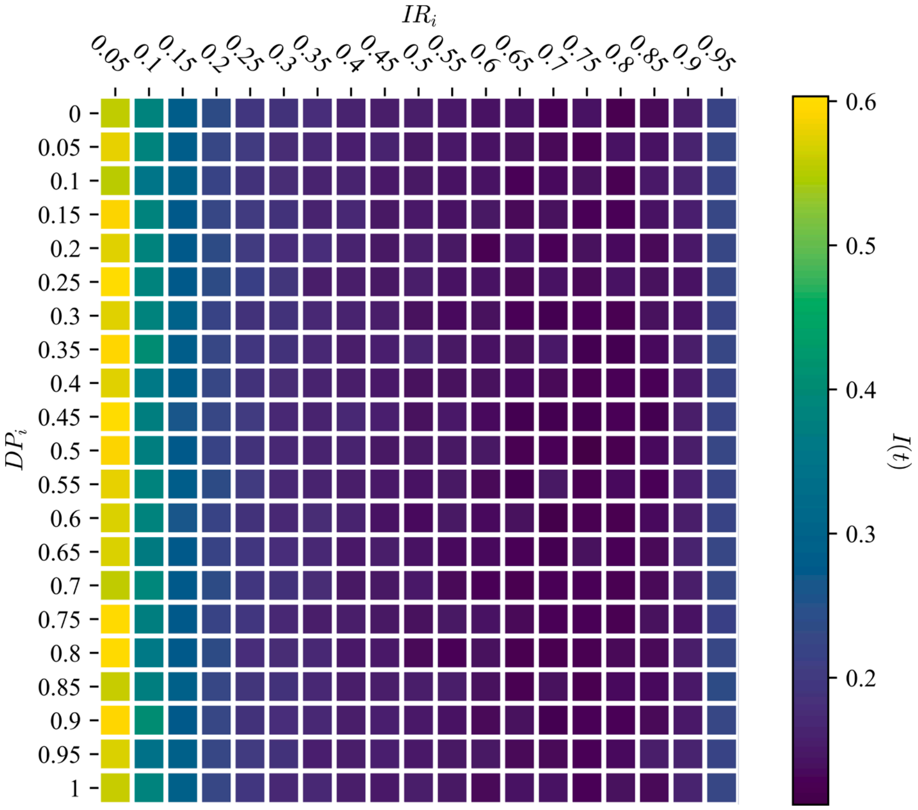

Fig. 7. Average institution application rate at the final time step for 100 simulations of each modeling scenario.

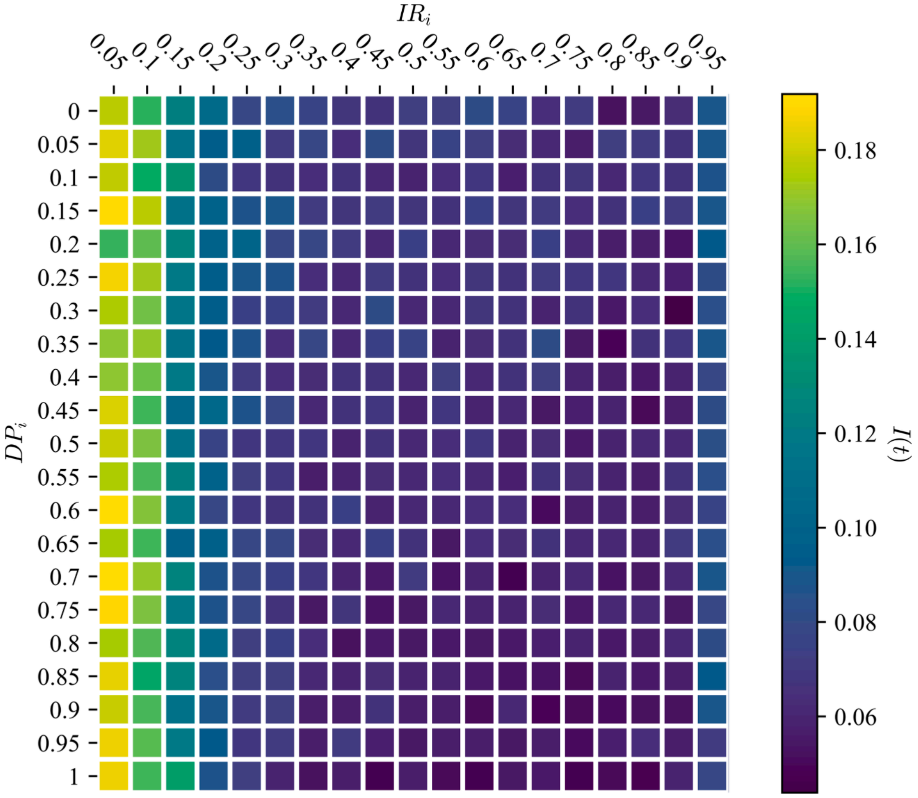

Fig. 8. Standard deviation of institution application rates at the final time step for 100 simulations of each modeling scenario.

change their willingness to random values.

The concentration of salt in the vadose zone is also assessed to explore and understand emergence of the institution. The average salt concentration in the vadose zone at the final time step of 100 simulations is shown for each modeling scenario (Fig. 9). While the institution application rate is insensitive to defection, the salt concentration increases with higher rates of defection. Although the institution application rates are similar across defection rates, the number of agents that do not comply with the institution and use their value for willingness results in high levels of salt in the vadose zone. Innovation rates of 0.05 and settings in the lower left-hand quadrant lead to salt concentrations that do not meet the limit specified at 30 g/m^3. For example, at an innovation rate of 0.10, the institution application rate ranges from 0.35 to 0.41 (Fig. 7). The salt concentration meets the standard for defection rates at or below 0.50 and does not meet the standard for values above 0.50. The standard deviation of the salt concentration also increases with increasing rate of defection (Fig. 10), indicating that there is predictability associated with low rates of defection and less predictability of results for high rates of defection. At higher innovation rates, increasing the defection propensity leads to higher variability in final vadose zone salt concentration.

Three modeling scenarios are compared to illustrate how defecting and innovation rates impact institution stability, final salt concentration, and final energy state (Fig. 11). The Low Defection Scenario uses low defecting and moderate innovation setting (10% likelihood to defect, 50% likelihood to innovate). The High Defection Low Innovation Scenario uses settings of high defecting and low innovation (90% likelihood to defect, 10% likelihood to innovate). The High Defection High Innovation Scenario used high defection and high innovation settings (90% likelihood to defect, 90% likelihood to innovate). For the Low Defection Scenario, the salt concentration remains mainly below the taste threshold across the simulated time horizon for the simulations, with gradual increase over time. For the High Defection Low Innovation Scenario, high rates of defection lead to high salt concentrations that exceed the threshold in almost all cases. A small number of simulations demonstrate a divergent behavior, and salt concentrations remain below the threshold. For these simulations, the low innovation rate indicates that agents did not randomly select new strategies, but copy willingness from connected agents. As a result, all 100 agents have very similar values for willingness, and for a few of these simulations, agents share low values for willingness, which lead to low salt concentrations. Finally, the High Defection High Innovation Scenario results in many simulations below the threshold. While the high rate of defection led to high amounts of salt released to the vadose zone, high rates of innovation allow agents to search for strategies that increase energy and reduce salt loads.

5. Discussion

This research develops a new agent-based modeling approach to simulate the emergence of institutions that limit stakeholder application of deicers in response to winter weather. While the use of deicer can improve the economic standing of households and businesses, overuse of salts can degrade freshwater resources, as observed in inland reservoirs across the U.S. Kaushal et al. (2018). This research applies an existing framework to operationalize Ostrom's theory that institutions can avert the freshwater salinization syndrome (Grant et al., 2022), which is one instance of the tragedy of the commons. The agent-based modeling approach adapted the SONICOM framework Ghorbani et al. (2017) to formulate and simulate decision-making about deicer application at private properties and salinization of water in the vadose zone. The framework uses calculations of salt fate and transport within the vadose zone to provide feedback to stakeholder agents that freshwater resources are becoming salinized, and agents cooperatively vote on institutions to adopt limitations on the amount of deicer that can be applied. Across simulations, the landscape and climate characteristics do not change.

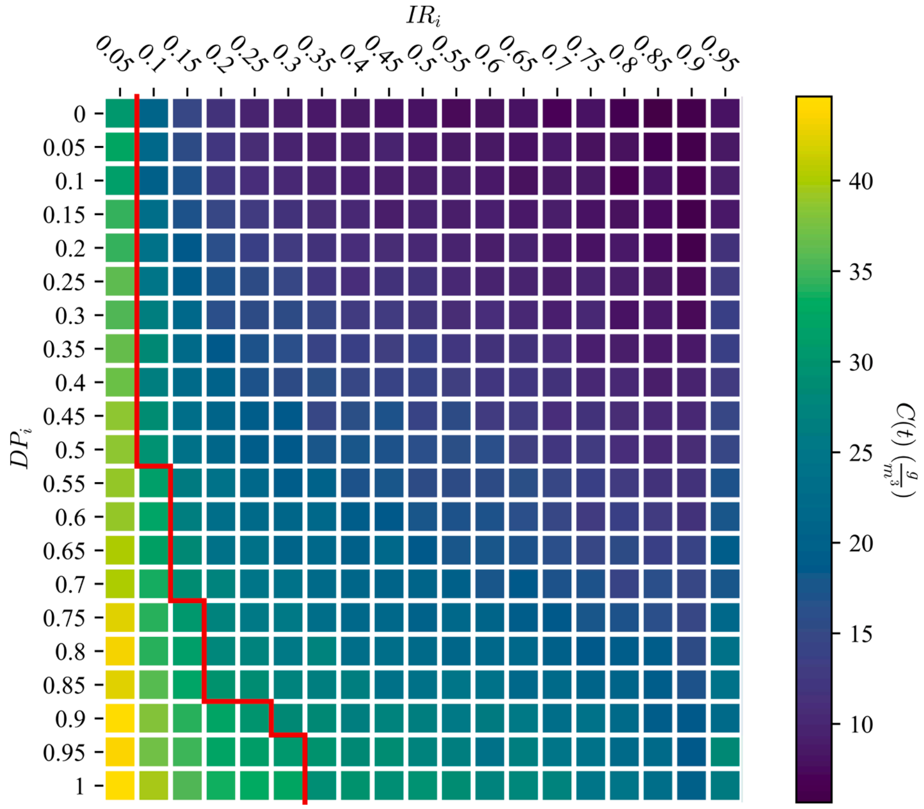

Fig. 9. Average vadose zone salt concentration at the final time step for 100 simulations of each modeling scenario. Red line separates heatmap based on the taste threshold. Upper-right envelope is below the taste threshold.

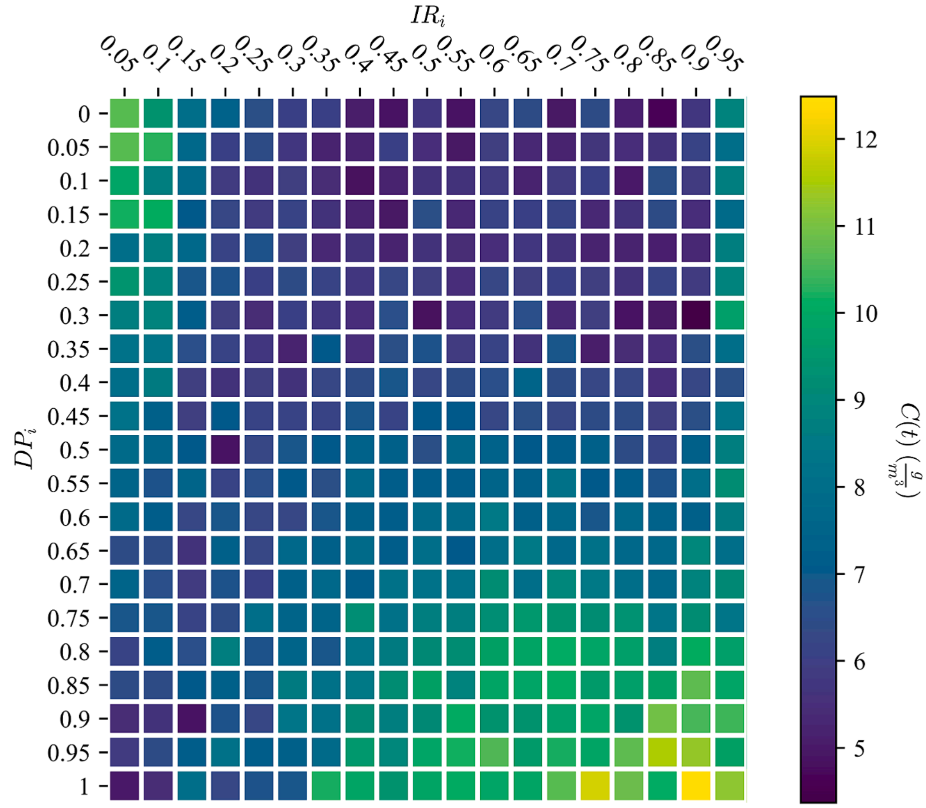

Fig. 10. Standard deviation of the vadose zone salt concentration at the final time step for 100 simulations of each modeling scenario.

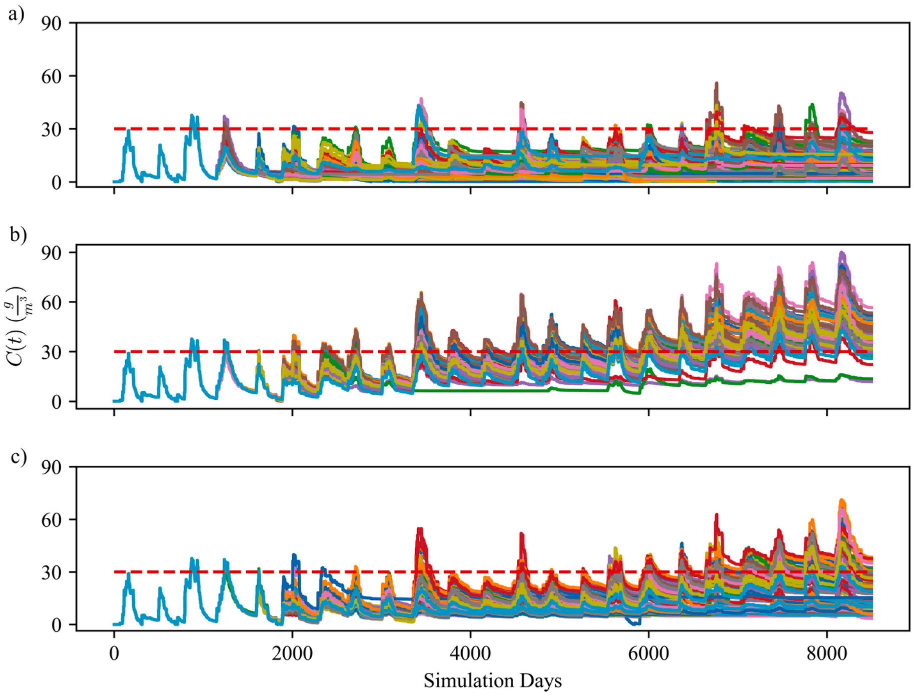

Fig. 11. Vadose zone deicer concentration for 100 simulations of modeling scenarios (a) Low Defection Scenario: 10% defecting and 50% innovation, (b) Low Innovation High Defection Scenario: 90% defecting and 10% innovation, and (c) High Defection High Innovation Scenario: 90% defecting and 90% innovation. Within each subplot, each colored line represents a unique simulation.

Adopting institutions that limit deicer application to 10–20% of common guidelines for deicing sidewalks after winter weather events typically ensures that the concentration of salt in water resources does not exceed the taste threshold. Higher frequency of defecting from the institution limits leads to high levels of deicer in the vadose zone. The propensity of agents to imitate agents that are in their network of peers leads to more stable, predictable outcomes. This modeling framework and the results it generates can be used in decision-making around salinizing water bodies. Decision-makers can assess the costs, water quality, and time horizon that are required for regulation and institutions to select strategies moving forward. Agencies can select, for example, to invest in workshops and meetings to allow stakeholders to engage and share information. Decision-makers can use modeling results to set an expected value on the number of stakeholders that must cooperate to achieve water quality targets. Further modeling can explore the type and frequency of social interactions that must be invested into reach water quality goals.

This research explored the effects of defection and innovation propensities on the reversibility of FSS. Cooperation among stakeholders is critical in developing institutions, and this modeling approach can be applied to identify the level of cooperation that is needed to ensure that salt thresholds can be met. Less compliant communities can lead to less predictable vadose zone recovery and higher concentrations of salt in waterways. This framework can be used to motivate communities around issues of salt management. Wutich (2009) found that water resources managed with stable and enduring institutions were more resilient to severe resource distress. Communities of stakeholders can be encouraged to implement deicer institutions, overcome legacy salt accumulation, and maintain salt levels below the taste threshold.

The SONICOM framework was developed in previous research; this research applied the SONICOM model to formulate the emergence of institutions within the context of FSS. This study developed a conceptual model and demonstrated it for a small illustrative case study. The case study was motivated by new research that characterizes the stakeholders and hydrologic processes governing salinization of the Occoquan Reservoir in northern Virginia (Grant et al., 2022). While the science around the contribution of salt sources and flowpaths in complex combined watersheds and sewersheds is still emerging, this research positions a new framework that can adopt hydrologic modeling frameworks as are developed to characterize complex ecological and social modules. Further research is needed to extend the model and develop actionable insight for developing guidelines and best practices for reversing the FSS.

The implications and limitations of the modeling decisions that were adopted in this research are discussed as follows.

5.1. Emergence of institutions

This research applies an agent-based modeling approach to explore the emergence of institutions. The results demonstrate that for most rates of defection and innovation, the institution reaches a salt application rate of approximately 0.10 to 0.20, indicating that property-owners agree to apply 10–20% of the required salt specified by best management practices. This institution is able to maintain the salt concentration below the threshold for a community with high rates of innovation and low rates of defection. These results demonstrate the institution that is expected to emerge among a community of property-owners, represented by the parameters encoded in the model. Attributes such as defection and innovation are difficult parameters to specify with precision, and this research demonstrates the effect of those parameters on modeling outcomes and the robustness of the institution when these parameters are specified without precision. The emergence of the institution relies on other parameters, including the number of property-owners, the characteristics of lots and land use, the economics of applying salt and of contaminated water supply. These values can be specified through development of a realistic case study. Future research can explore the interactions among other parameters and their impacts on the emergence of institutions.

All agents are initialized with salt application willingness set at 1.0 to represent stakeholders who are initially not aware of the FSS. The institution that emerges depends on the initial values for agent willingness, because the contamination of the water supply drives decisions to adopt an institution. Initializing agents at lower values to represent stakeholders that limit their salt application may not generate high enough salt concentration values to prompt the formation of institutions. Further research can explore the relationship of the institution with initial salt application willingness values. In the SONICOM model, agents vote on sanctions, or fines, and monitoring rates. These parameters are not adjusted by agents in response to economic or environmental feedback in the same way that the salt application rate is adjusted. Future research can simulate agents that use feedback to update their beliefs around monitoring and fines.

This framework simulates that agents vote on institution characteristics, including limitations, fines, and monitoring intensity on a monthly basis. Institutions are not initiated until the salt concentration exceeds the taste threshold. In realistic settings, however, stakeholders may be catalyzed to act by rising salt concentrations. Proximity to the taste threshold can be used as a trigger to activate institutions to allow stakeholders to avoid exceeding salinity limits. Future research can develop new modeling rules to represent stakeholders and property owners that react to rising salinity levels.

5.2. Hydrologic modeling

In the formulation that is implemented through this research, agents change and interact with salt concentrations, but they do not change or interact with hydrologic flows. Some controls for salt may focus on changing land use, such as reducing the area of land for impervious surfaces or facilitating smart growth development. These management strategies would not only affect the salt application, but also change the hydrologic flows. The TTD modeling approach adopted here can be adapted to update hydrologic flows and solute transport in response to not only decisions about deicer application rates, but also decisions about land use and land cover changes. The TTD model approximates the salt concentration as one value across the stakeholder inputs, and further modeling is needed to capture the spatial variation in salt concentration and how spatial variation intersects with the location of different stakeholders.

This research simulates salt transport in the vadose zone to represent the interaction of stakeholders with water resources systems. Further research should couple the framework with large complex water resources systems to capture the pathways of salt transport that include watershed runoff, hydraulic flows in stormwater sewer systems, groundwater infiltration, and circulation in reservoir systems. Comprehensive water resources and water infrastructure models can more realistically capture the dynamics of salt concentration in water supply sources that serve as signals for stakeholders to adopt institutions.

5.3. Stakeholder modeling

Stakeholder agents are modeled in this research to represent homogeneous small business owners, and this study did not consider other sources or salinity or other environmental systems such as ponds or estuaries. This research investigates the emergence of institutions within the context of a single source of salinity to explore the influence of the emergence of new norms within a small watershed environment. This research was motivated and conceptualized based on the salinization of the Occoquan Reservoir Grant et al. (2022), which involves stakeholders including communities, state departments of transportation, water treatment utilities, and industries. Future research can explore how institutions develop in a broader definition of salinization and include stakeholders who use salt products, such as fertilizers or detergents, that impact groundwater salt assimilative capacity. Heterogeneous agents can be created to represent the range of decision-makers that contribute to and are affected by the FSS. New research is needed to develop data to characterize salt loads, costs of reducing salt contributions, and costs of salinized water supply for diverse stakeholders. Further, residential communities contribute to salinization through the use of fertilizers, detergents, and other household products Grant et al. (2022). Households may not be engaged in institution-based limitations, and a hybrid approach that develops agreements on salt limitations may need to incorporate a regulatory approach to pass restrictions on to households and businesses. Developing agents that represent diverse community members and simulating their interactions and decision-making may assist policymakers in identifying agent groups that have a critical impact on watershed vulnerabilities. Accurately describing agent characteristics and group interactions can lead to more realistic descriptions of institution stability. Further research and development of the framework can explore the dynamics of social influence, negotiation, regulations, and collusion that may affect the emergence of institutions. A participatory approach that uses cyclical interactions to characterize stakeholders and share modeling results can lead to refined scientific insight about salinization and improved cooperation among stakeholders.

The modeling framework uses a simple representation of a social network. More complex network structures that allow agents to add or remove connections can more realistically represent the formation and adoption of new strategies in social systems. The model formulation used in this research assumes that agents know all strategies and defection decisions within their social networks. This assumption can adequately represent a range of social systems. In agent-based models that simulate imitation around decisions to defect, agents observe or see the behaviors of other agents, implying that agents physically watch other agents or directly exchange information about decisions (Axelrod, 1986; Castilla-Rho et al., 2017). Grant et al. (2022) found that through in-person interviews and meetings, where stakeholders could converse with minimal transaction costs, stakeholders exchanged information about compliance and identify existing norms in the context of the FSS in the Occoquan Watershed and Reservoir. This interaction led to the emergence of new norms as stakeholders collaborated and shared their experiences with FSS (Grant et al., 2022). Schaat et al. (2017) found that the sustainable behavior and attitudes of agents can be influenced by social media, which implies that agents physically separated can still be influenced by other agents if they can monitor their social media activity. Future research can also explore different levels of agent knowledge and observation to represent other social systems. The SONICOM model developed by Ghorbani et al. (2017) used two scenarios for social network initialization: a ”random” network where agents maintain static connections to other agents throughout the simulation, and a ”small world” network which simulate agent networks that are more likely to form based on proximity. In this research, we simulate ”random” networks alone because agents are not assigned spatial locations within the watershed, and, as a result, there is no metric of proximity. In future applications, agents can be assigned geographic coordinates. Social networks can be comprised of neighbors, where agents can physically see and observe other neighbors’ strategies, similar to agent-based models that simulate landowners as agents that manage parcels of land and update decisions based on spatial proximity to other agents, land use history, and planning for future land uses (Matthews et al., 2007). Future research can spatially locate agents and determine the impacts of their spatial distribution on vadose zone salinity, as well as simulate neighboring agents that exchange deicer application strategies and observe defection.

6. Conclusion

This research developed a computational model to simulate the impact of stakeholder deicer application decisions on the salinity of a shallow groundwater used as a drinking water supply. An agent-based modeling approach was adopted that represents property owners as agents. The agent-based model was coupled with a transit time model to calculate salinity of water discharged from the vadose zone under unsteady inflows from rain and snow melt. An agent-based modeling approach captures the complex interactions and feedback mechanisms among various stakeholders involved in deicer application decisions. Agents adopt new salt application strategies, imitate their peers, vote on limits to enable an institution, and choose to defect. Defecting agents are punished through sanctions, and agents adopt new behaviors based on economic feedback. The framework was applied for an illustrative case study to explore how deicer application institutions emerged and stabilized salinity levels. Deicer application decisions lead to deicer institutions, or limitations on the amount of deicer that can be applied. Institutions have a significant impact on groundwater salinity and consequently the soil and groundwater quality. This analysis sheds light on how deicer application institutions emerge and stabilize over time. Results demonstrate that the emergence of stable institutions is closely linked to the adaptive behavior of property owners and their willingness to cooperate. Agents vote and adopt an institution that limits salt application to 10–20% of the required salt specified by best management practices. Higher propensity to defect from institutions led to higher variability in the limitations imposed by institutions, and low rates of innovation limited the ability of the institution to achieve salt concentration goals. The modeling approach developed in this research can be applied to manage salinizing water bodies. The agent-based modeling approach can be used to assess the cost and performance of institutions that can emerge to create a comparison with regulations. Decision-makers may select to invest in participatory activities for stakeholders to facilitate cooperation and achieve water quality goals.

The agent-based modeling framework can be extended to larger watersheds with higher degrees of heterogeneity to further explore the emergence of institutions in the context of the FSS. Institution stability can be assessed through statistical time series approaches to identify parameter values and case study characteristics that lead to institution instability. Applications of this framework to large complex systems that encompass reservoirs, sewersheds, and watersheds can provide insights into the dynamics of salt management policies and salt assimilative capacity. The agent-based modeling framework developed in this research can be an effective tool for modeling complex water resources systems to assess environmental management and policy-making for sustainability. This framework can be used to assist policymakers and stakeholders in making informed decisions and promoting sustainable deicer application practices.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.hydroa.2024.100188.

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