**PROJECT TITLE**

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**Summary**

Salt is a widespread, serious, and growing pollution problem that compromises water quality and harms aquatic life. Levels of salt pollution in many fresh surface waters in the United States now exceed the EPA chronic exposure criteria for chloride. Despite its simple chemistry, salt is also among the most difficult substances to remove by any practical conventional form of water treatment, and it can be a significant impediment to water reuse for irrigation or drinking. Salt behavior in our watersheds is perplexing. Salt has generally been considered to behave relatively simply, and indeed at low levels it is merely transported with water. Yet at higher concentrations, unexplained outcomes occur. For instance, careful mass balance studies conducted on relatively large watersheds have unexpectedly found that a majority of deicing salt can be unaccounted for on timescales of years and much salt is thought to reside in groundwater stores. Salt also alters the physical characteristics of water, increasing its density, and leading to stratification. Finally, we have observed salt to appear in pulse exports in streams long after the deicing season has ended.

Here, we investigate some of these surprising behaviors by modeling salt residence times in and through various surface and subsurface stores within a **S**mall **Wa**tersheds with **R**esidential **D**evelopment (which we dub SWaRDs). In particular, we posit that the subsurface in SWaRDs along with their numerous catch basins can harbor dense concentrations of saline water that can explain some of the “missing” salt, and the delays and pulses in delivery seen by us and others.

Our preliminary results suggest that salt storage in small surface waters and groundwater stocks plays a significant role in creating lagging export dynamics. We also find that stormwater management ponds and catch basins can harbor substantial volumes of salt that contribute to watershed storage and lag. Finally, we show that salt toxicity for one species of amphibian is dependent on temperature, suggesting that salt stress on biota in the wild likely interacts with numerous other stressors caused by human activities.

**Introduction**

Many urban, suburban, and even rural watersheds throughout the U.S. (including Connecticut) are heavily and increasingly polluted by salt (Brady 2012; Corsi et al. 2015; Godwin et al. 2003; Kelly et al. 2007; Mullaney 2019). Common sources of salt pollution include agriculture, wastewater, industry, dust suppression, but most substantially, deicing of roads, parking lots, and walkways2,16. In the last decade, annual NaCl used for deicing salt ranged from about 15 – 32 million metric tons, twice the amount applied four decades ago17,18

Salt-polluted surface and ground waters do not behave identically to unpolluted waters, as has often been assumed. Rather, salt lingers in watersheds. Mass balance studies have found that about 40-70% of deicing salt applied each year does not leave the watershed within that year (Novotny et al. 2009; Perera et al. 2013). Stated another way, about half of each year’s deicing salt is being held somewhere in the watershed. The duration of storage is uncertain, but one estimate suggests that if all deicing stopped, chloride concentrations in rivers would continue to influence downstream salt levels for 20-30 years (Kelly et al. 2019). More directly, in some systems, including ones that we have measured, summer salt levels in tributaries are higher than those in winter, implying a delay of at least 6 months (Kelly et al. 2019). Summer baseflows can also see surges of salt, unexplained by prevailing assumptions of salt transport. These patterns reveal that **fundamental properties of watershed salt storage and export remain poorly understood**, prompting important research questions: Where and under what conditions is salt being detained? For how long? How often is salt released from these stores? And what triggers salt to be released in pulses like those we have documented?

Many mass balance studies have tended to apply simplified approaches to understanding salt movement through watersheds, often contrasting stream baseflows with non-baseflows to parse the amount of salt stored in and exported from groundwater versus surface and subsurface waters. While some studies apply more exact approaches by measuring groundwater directly, they generally neglect small surface waters (SSWs)—such as small lakes, ponds, pools, and even catch basins. Yet SSWs can hold substantial volumes of water, and dense salt pollution entering SSWs can be delayed from traveling down system. Some SSWs, even shallow ones, can become stratified with dense, salty bottom waters (Brady 2012; Novotny et al. 2008; Wiltse et al. 2020), which delays export while allowing more salt to enter groundwater. Turnover events in stratified SSWs could potentially generate strong pulses of salt downstream. These roles of SSWs are particularly relevant in small watersheds with residential development (SWaRDs), where salt concentrations can vary dramatically over short periods of time, in contrast to higher order rivers where local dynamics become dampened. Indeed, pulse inputs coupled with the above-described dynamics could translate into large swings in salt concentrations throughout the year. SWaRDs also often contain a mixture of natural water features and best-management practice (BMP) SSWs, including detention ponds and catch basins. And while each catch basin is small, in aggregate these BMPs can store and release substantial amounts of salt. **We therefore contend that SSWs and their unique features are likely playing neglected, important roles that interact with groundwater dynamics. We posit that these roles can explain previously unaccounted for fractions of “missing” salt and help resolve puzzling dynamics of export, particularly at the key spatial scale of SWaRDs.**

**Objective(s)**

1. Begin to assess the role of groundwater storage in the “missing” salt quandary
2. Characterize salt storage and transport in SSWs, especially catch basins
3. Link local processes to regional patterns
4. Characterize biotic responses to salt pollution

**Results/Discussion**

Here, we provide preliminary results from different components of our study.

***Catch Basins***

We have installed V notch weirs and conductivity/depth loggers in three catch basins at the Hamden Hills housing development. Instruments are located at the surface and the bottom of the sump to understand salt dynamics in these systems, of which there are more than 100. Although the sumps are only 0.5 m deep, there is a dramatic disconnect between salinities at the surface and bottom of these systems, and conditions persist year round. For example, data from catch basin TW 40 in late Fall 2021 That the bottom of the sump (green line) is a salty brine with a specific conductance near 8,000 uS/cm. Water near the surface (yellow) is less salty, but still high (~ 1000 uS/cm) above regional baseline values (typically 20 uS/cm), especially after a storm on 13 December. The blue line is water depth, which we can use with the V notch weir to reliably calculate discharge. Interestingly, conductivity at the top of the catch basin exceeds that at the bottom at the very end of the record. This reversal may be mediated by differences in temperature which also influence density.

***Main pond/Outlet***

Rain on impervious surfaces at HH flows first across roadways and into catch basins. It then travels to three BMP ponds and a large natural pond/wetland complex before draining to a small stream and entering Shepard Bk, a tributary of the Mill River. The graph of the Town Walk outlet (TW is part of the Hamden Hills development) shows a typical, and perhaps unexpected pattern in Fall 20****21. Conductivity (green symbols) is high, with levels close to 800 uS/cm. Individual storm events (spikes in the blue trace showing depth in the outlet weir) cause temporary dips in conductivity but rapid returns to prior saltiness. Even Hurricane Ida and a nor’easter in late October did not significantly “flush” salt out of the development. We believe this salt is retained in catch basins, BMP ponds, and groundwater. Notably, there was no salt applied to roads for about 6 months prior to these measurements.

***Tributaries***

At various times during the study, we have monitored three tributaries of the Mill River, which is monitored by the USGS (USGS 01196620 Mill River Near Hamden, CT) as part of their national network. Shepard Bk has mixed land use and is the tributary into which the outlet from Hamden Hills flows (just upstream from the tributary sampling site). The figure shows water depth (in the river) and specific conductance for the period from summer – fall 2021, a period with no road salting. During this interval there were three rain events of at least 10 cm, Hurricanes Elsa and Ida and a Nor’easter in October. Remarkably, these storms, plus many others documented on the graph (spikes in depth) had almost no long term effect on salt (conductivity) in the tributary; levels quickly returned to pre-storm values within a few days. This behavior attests to the persistence of salt distributed throughout the watershed.

***River***

 Although the USGS monitors the Mill River, it is at a site about halfway down the length of the river and upstream of our main study site, Hamden Hills. For that reason, we monitor depth and conductivity near the river’s mouth. We have also established a rating curve based on Doppler flow meter measurements to convert depths to discharge. Data are shown for the period from summer 2020 through spring 2021. Perhaps surprisingly, salt levels remained high throughout this period, typically close to 400 uS/cm. Also oddly, the lowest values recorded were during winter (roughly Nov – Jan).

***Wells***

We suspect that a significant portion of “missing salt” can be found in groundwater, though sampling the subsurface is difficult. We identified a section of the Jepp Bk watershed where several houses use drilled wells as a water source. Jepp Brook is a tributary of the Mill R that enters upstream from Sheppard Bk. Homeowners agreed to let us sample their well water, which we have been doing roughly monthly. Results show that groundwater in this tributary’s watershed are elevated compared to background levels, but are below amounts we find in either Sheppard Bk or the Mill R as a whole. (Note: the black bars are from wells located outside and upstream from the Jepp Bk watershed.) However, salt readings in the wells are similar to levels we measured in the past in Jepp Bk itself. This is consistent the idea that surface waters may be closely coupled with groundwaters

***Biological effects***

Salt is just one of many stressors that wild organisms face. Not surprisingly, multiple stressors (e.g., thermal stress from climate change, disease, other pollutants) can interact to shape the toxicity and ultimately the fate of populations exposed to salt pollution. At the same time, salt toxicity can vary as a function of population exposure history, for instance with roadside populations perhaps having the capacity to adapt to salt over many generations of exposure. Here we report that salt stress and thermal stress interact. The figure below shows that salt toxicity is temperature dependent, with elevated temperature increasing the toxicity of salt for populations of the wood frog (*Rana sylvatica*), both in terms of survival (left panel) and **developmental rate (middle panel). Interestingly, salt stress in the wild appears to be correlated with tolerance to temperature, with frogs from salt-polluted roadside populations showing an increase in thermal tolerance (‘CT max’).

**Conclusions**

Salt pollution remains a serious and indeed growing threat to ecosystem health. Yet basic knowledge of its movement through watersheds remains poorly described. Here, show that common surface waters, including both natural features and those modified for management, can serve as important stores of salt, contributing to its lagging export dynamic. We draw similar conclusions about catch basins, which while small, are numerous in developed landscapes, and can also store substantial amounts of salt. Finally, we highlight the important role of groundwater as a store of salt, and in particular, its resilience against dilution from storms, whereby even anomalously high rainfall events have only a fleeting effect on the concentration of salt found in our streams and groundwaters.

**Acknowledgements**

Include if necessary.

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