

EFFECTS OF CLIMATE CHANGE AND PHARMACEUTICALS AND PERSONAL CARE
PRODUCTS ON NITROGEN REDUCTION EFFORTS IN THE LONG ISLAND SOUND
WATERSHED

by

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DEDICATION

To Neal: your unconditional companionship, support, and unwavering optimism made this degree possible.

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ABSTRACT

Nutrient enrichment of surface waters can lead to harmful algae blooms and hypoxic events in estuaries which is a concern in the New England region. Long Island Sound is an estuary bordered by Long Island, NY, and Connecticut with a history of nitrogen enrichment from wastewater and stormwater runoff. My paper focuses on the impacts of climate change and pharmaceuticals and personal care products (PPCPs) on nitrogen reduction efforts in the Long Island Sound watershed. To understand these potential impacts, I searched for scientific papers from major repositories using questions regarding the relationships between precipitation, surface runoff, CSO events, nitrogen loading, and the potential synergetic effects of climate change, plus the impact of PPCPs on bacterial nitrogen reduction. I then conducted a literature review and analysis of the articles to establish their findings on these relationships. Afterwards, I conducted a case study on four urban Connecticut districts with CSOs, analyzing their urban cover, precipitation, and CSO events to substantiate the relationships. The analysis of the literature established that surface runoff from precipitation on impervious surfaces is a main contributor to CSO events and subsequent nitrogen pollution. Furthermore, climate change is predicted to increase heavy precipitation, subsequently increasing stormwater and CSO volumes, and the concentration of conveyed pollutants. Results from the case study indicate an increase in the intensity of impervious surfaces and an increase in the average monthly rainfall (0.17 inches; March to September) in the studied districts. Also, a statistically significant relationship between rainfall and CSO events was found for the districts of Bridgeport and Norwich. Lastly, common PPCPs found in wastewater such as antimicrobials can have an inhibitory effect on bacterial nitrification and denitrification processes. Mitigation strategies to address stormwater runoff in urban areas should be targeted and applied at different spatial scales for the greatest effect. More study is needed using direct measurements of rainfall, stormwater, and CSO discharges to better understand their relationship and conveyance of nitrogen to surface waters. Moreover, direct testing for common PPCPs in wastewater is needed to ascertain current concentrations and their potential effects on nitrogen reduction during wastewater treatment.

INTRODUCTION

Southern New England estuaries have the unfortunate distinction of being among the most eutrophic in the United States (Gedan et al., 2011). Bordered on and enclosed by the coastlines of Long Island, NY, and the state of Connecticut, Long Island Sound has limited circulation in the western end and is historically eutrophic. Long Island Sound has a history of hypoxic conditions resulting from nutrient enrichment and low dissolved oxygen concentrations during the summer months (Connecticut Department of Environmental Protection, 2000). Research and monitoring efforts for eutrophication and resulting declines in ecosystem functions within the sound date back to the mid-1980s (Connecticut Department of Environmental Protection, 2000).

Eutrophication is the condition of an aquatic system with elevated nutrients from human activities such as organic nitrogen, ammonia, and nitrate. Estuary systems like Long Island Sound are nitrogen-limited environments; an influx of nitrogen into the sound stimulates rapid photosynthesis and growth of the algae known as blooms. The algae blooms eventually die and fall to the bottom of the sound. As they decompose, biological oxygen demand increases, proportionally decreasing dissolved oxygen in the water. As the surface water in the sound warms during the summer, the warmer water temperatures cause a distinct stratification between the surface and bottom water preventing vertical circulation (Long Island Sound Study, 2023). This stratification, along with the decrease in dissolved oxygen in bottom waters from the decomposition of dead algae, fuels hypoxic events (Long Island Sound Study, 2023). Hypoxia often results in the death or emigration of marine organisms, disrupting the sound's ecological function. Likewise, the cultural and provisional services provided to the region by Long Island

Sound are diminished by increased turbidity due to algae, lowered oxygen levels, and increased frequency of toxic algae events (Connecticut Department of Energy and Environmental Protection, 2019).

Connecticut is a dominant contributor of nitrogen to Long Island Sound via three large riverine watersheds (Connecticut, Thames, and Housatonic) (Fig.1) that carry accumulated nitrogen from atmospheric deposition, land use practices via surface runoff, and groundwater return flow, wastewater treatment effluent, and combined sewer overflows (CSOs) (Connecticut Department of Environmental Protection, 2000). Point source pollution from wastewater treatment effluent and CSOs constitute the largest nitrogen load to Long Island Sound from these watersheds (Connecticut Department of Environmental Protection, 2000).

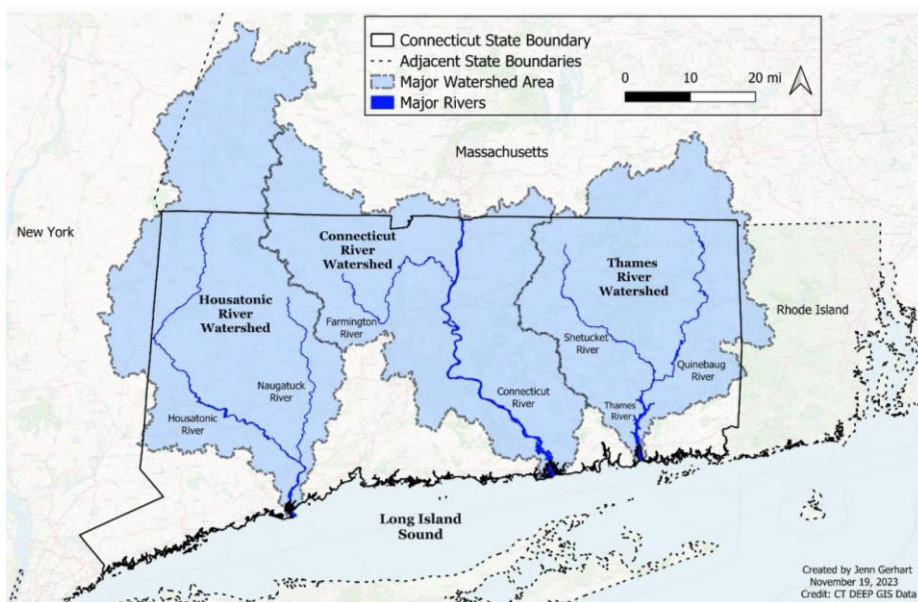


Figure 1. Major Connecticut watersheds that empty into Long Island Sound.

Combined sewer overflows are events where untreated wastewater and stormwater are released into local waterways. Sewer systems that were designed to carry both wastewater and stormwater are called combined systems. These combined systems have built-in overflow valves at points along the conveyance route to the local wastewater treatment plant. During precipitation events such as rain or snowmelt, the water flowing into the stormwater drains combines with the wastewater and can exceed the capacity of the sewer system. When the volume of water in the system is greater than its capacity, the excess untreated waste and stormwater discharges into a local stream thus causing a combined sewer overflow event (Fig. 2).

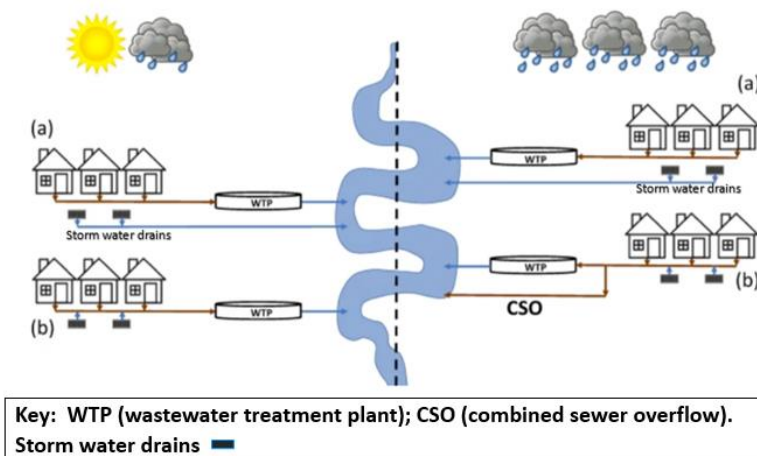


Figure 2. Separate (a) and combined (b) sewer systems. Pathways under dry-weather (left side) and wet-weather (right side) conditions. (Fig. 1 in Petrie, 2021)

Over the past two decades, Connecticut has focused its nitrogen mitigation efforts on point source wastewater treatment effluent, with the state spending an estimated \$720 million to add biological denitrification capabilities at its wastewater treatment facilities to reduce nitrate-

nitrogen in effluent. These denitrification additions to the treatment process use an anoxic tank where facultative anaerobic bacteria convert the nitrate in the wastewater to nitrogen gas (Chapin et al., 2012). The investment to increase the denitrification of wastewater has allowed Connecticut to meet its 2000 Total Maximum Daily Load (TMDL) nitrogen reduction target since 2012 (Connecticut Department of Energy and Environmental Protection, 2019). Recent efforts in mitigation of nitrogen from point sources include the reduction of CSO events within the urban districts of Metropolitan Hartford, New Haven, Bridgeport, New Haven, and Norwich through options such as decoupling combined sewer infrastructure where feasible and increasing capacity of wastewater treatment facilities (Connecticut Department of Energy and Environmental Protection, 2023). Retention storage is part of the long-term CSO control plans for Metropolitan Hartford and New Haven. Retention along the sewer conveyance route would hold and temporarily store CSO volumes and then return them to the sewer flow during dry weather periods for treatment at the local wastewater plant (USEPA, 1999).

Despite more than \$1 billion spent or allocated to total nitrogen reduction and having met their TMDL wastewater reduction target for nitrogen since 2012, intensified impervious cover (Gedan et al., 20011) and extreme precipitation due to climate change (Huang et al., 2021) in Connecticut may directly increase the volume of stormwater and CSO discharges and convey greater concentrations of nitrogen to its surface waters (Suchowska-Kisielewicz & Nowogoński, 2021; Salerno et al., 2018). The mean trend for impervious surface cover in Connecticut from 1975 to 2011 was > 1% per year (Torbick & Corbiere, 2015). Urban districts within Connecticut (Metropolitan Hartford, New Haven, and Bridgeport) have > 50% developed urban cover (Torbick & Corbiere, 2015). Predicted impacts of climate change on the New England region

include more extreme precipitation events, including tropical storms (Huang et al., 2021). Extreme precipitation is a rainfall event that falls within the top 1 % of wettest days (U.S. Global Change Research Program, 2023). New England has experienced an increase in extreme precipitation at a rate greater than any other climate region in the United States, with a 77 % increase since 1958 and a marked increase since 1996 (Fig. 3) (Huang et al., 2021). The increased heating of the atmosphere and rising sea surface temperatures from climate change contribute to the rise in extreme precipitation (Huang et al., 2021). Projections for Connecticut include a rise in the total annual rainfall of one inch by the end of the century and more frequent extreme precipitation during winter and spring months (U.S. Global Change Research Program, 2018). In the future, the removal of nitrogen, such as ammonia and nitrate, by the wastewater treatment process may decrease if volumes of stormwater and combined sewer overflow discharges increase due to elevated precipitation (Huang et al., 2021; U.S. Global Change Research Program, 2018) and impervious cover (Torbick & Corbiere, 2015).

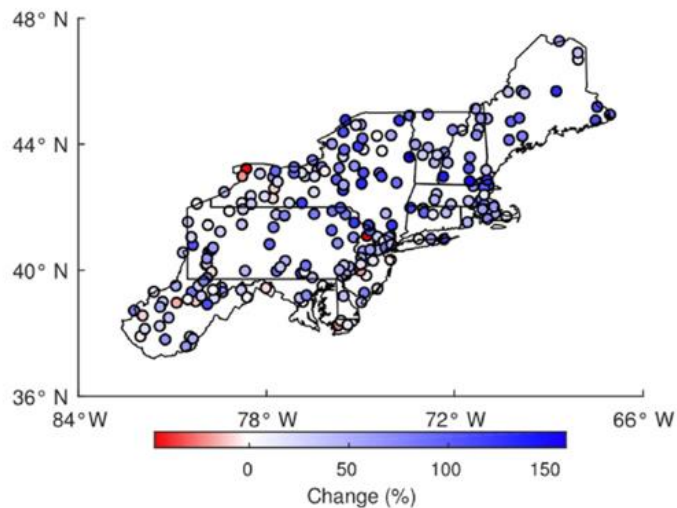


Figure 3. Relative change in annual extreme precipitation for New England. The change denotes the percentage difference between 1996-2019 compared to 1920-1995 using records from 220 Global Historical Climatological Network-Daily (GHCN-D) weather stations; each station had at least 80 % complete daily records from 1920-2018. (Fig. 1 in Huang et al., 2021)

Furthermore, pharmaceuticals and personal care products (PPCPs) found in wastewater might also contribute to increased nitrogen loads in effluent by hindering the efficacy of the removal of ammonia and nitrate from wastewater. Any products that individuals use for cosmetic or health reasons including cleansers, soaps, toothpaste, over-the-counter medications such as pain relievers, and prescribed medications such as antibiotics are considered PPCPs. Many personal care products get rinsed off our bodies and down our drains while portions of ingested pharmaceuticals get excreted in our waste; in addition, many people also dispose of PPCPs by flushing them down the toilet or drains (Illinois Sustainable Technology Center, 2023).

Pharmaceuticals and personal care products contain numerous chemical compounds and because there is little known about their impact on the environment, the EPA has categorized

them as contaminants of emerging concern (Illinois Sustainable Technology Center, 2023). Some chemical compounds in PPCPs can be toxic to bacteria resulting in reduced metabolic activity or increased mortality which could hinder or halt biological nitrogen removal processes during wastewater treatment (Lopez et al., 2021; Chen et al., 2017; Li et al., 2019; Robson et al., 2020; Tan et al., 2021; Wang et al., 2017; Xie et al., 2022). The nitrogen removal efficiency of current wastewater treatment, including expensive nitrate removal retrofits, may be reduced due to these chemicals, however, the potential threat of PPCPs was not well known until recently.

For this paper, I first conducted a literature review to understand the likely relationships between precipitation, surface runoff, CSO events, nitrogen loading, and the potential synergetic effects of climate change. I searched for scientific papers using various phrasing of the following questions related to these factors: What is the effect of precipitation on stormwater runoff and combined sewer overflows? What are the effects of stormwater runoff and combined sewer overflows on nitrogen pollution? What is the effect of climate change on precipitation and precipitation in New England? What is the effect of climate change on stormwater runoff, combined sewer overflows, and nitrogen pollution? From my searches, I was able to review and analyze the findings of 20 papers from major repositories. Then, I conducted a case study of four urban districts in Connecticut with CSOs, analyzing their urban cover, precipitation, and CSO events to corroborate these relationships. Next, I conducted another literature review using 10 scientific studies on PPCPs I found through searches for the effects of PPCPs on bacterial communities and the processes of nitrification and denitrification. I used the results to discuss potential declines in the nitrogen reduction capacity of Connecticut's wastewater treatment

plants. And, finally, I made recommendations for reducing stormwater runoff in areas with high numbers of CSOs by using the findings of 7 scientific papers from searches regarding the implementation of green infrastructure in urban areas to reduce stormwater runoff.

THE HISTORY OF COMBINED SEWER SYSTEMS AND THE RELATIONSHIP BETWEEN PRECIPITATION, SURFACE RUNOFF, AND CSO EVENTS

The immigration movement of the late 1800s and early 1900s saw the depletion of natural land cover in New England as housing and urbanization spread. For example, during the 100 years from 1830 to 1930, about 5,000 acres of coastal salt marsh and mud flats were filled for industrial and urban growth projects (Bromberg & Bertness, 2005). Today, urban development is still concentrated along the coasts but has also intensified along interstate highway corridors (Torbick & Corbiere, 2015).

Urbanized areas have extensive impervious surfaces like roads, sidewalks, and rooftops that change the hydrologic cycle. In undisturbed vegetated land cover, leaves and stems intercept rainfall, reducing the amount of water that reaches the ground. Rainfall that makes its way to the ground is easily absorbed and infiltrated through the litter layer and then into the soil, where the water becomes part of subsurface flows or transpires back into the atmosphere (Tarboton, 2023). Nitrogen deposited onto soil surfaces is moved with water infiltration down into the soil where the roots of vegetation remove much of the nitrogen via uptake and assimilation into tissues (Chapin et al., 2012). In contrast to undisturbed land, impervious surfaces associated with developed urban cover negate the infiltration of rainfall, resulting in overland flow, thus creating stormwater runoff. Stormwater runoff is positively correlated with land cover change. As the vegetated cover disappears at the expense of impervious surfaces, the amount of accumulated surface water and subsequent runoff increases (Alamdari et al., 2022). Nitrogen deposited on impervious surfaces is also collected with the stormwater and carried into nearby streams (Alamdari et al., 2022). Infrastructure in urban areas is designed to minimize the impact of

stormwater runoff that results from precipitation collecting on impervious surfaces by moving the collected water off streets and roads through a stormwater system. Stormwater systems can be a single dedicated system where collected surface runoff is channeled through a network of pipes away from the urban area and discharged into a nearby stream (Burian et al., 1999). These systems can also be designed to feed into the sewer system where the collected surface runoff becomes a part of the wastewater flow and is eventually treated at the local wastewater plant (Burian et al., 1999). Newer urban areas are built with separate systems for storm and wastewater, though older cities in Connecticut and New England still rely on combined systems (Fig. 4).

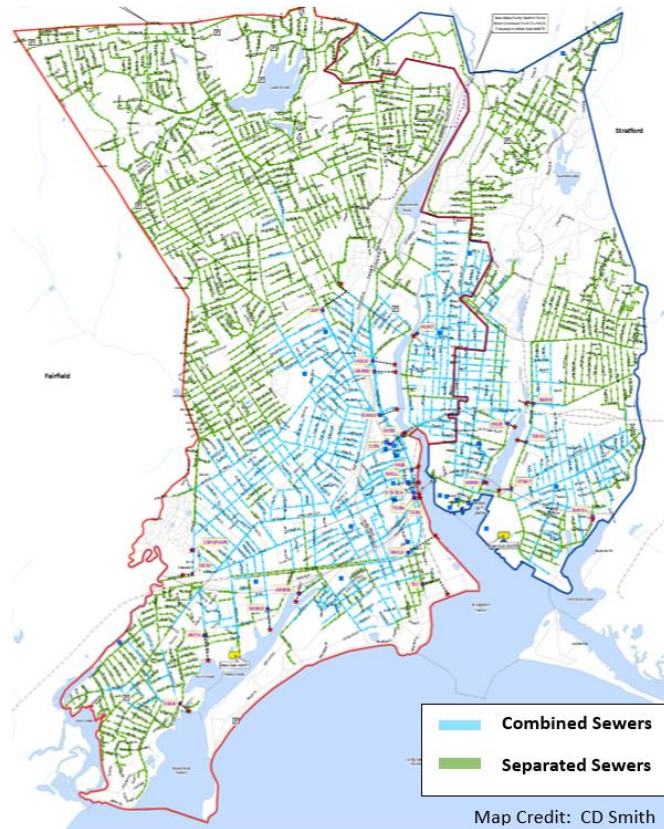


Figure 4. An example map of combined and separate sewer system networks in an urban area. (Fig. 2.3-1 in Raymond and Bighinatti, 2021)

During the urbanization boom of the 1800s to early 1900s in New England, the prevailing design to deal with urban surface runoff and wastewater was the combined stormwater and sewer system (CSS) (Burian et al., 1999). The CSS was thought at the time to be a more economical approach than having separate systems for storm runoff and wastewater, especially in large or rapidly growing cities. Designs for the combined systems at that time primarily dealt with the

volume of wastewater for the current population, however, it wasn't until the 1920s and after that CSS were designed to consider excess flows within the system from the addition of stormwater (Burian et al., 1999). Moreover, from the start, CSSs were designed to relieve excessive volumes by discharging untreated water into the environment (Burian et al., 1999). When high volumes within the CSS exceed the capacity of the pipes or the processing capacity of the connected wastewater treatment plant, the untreated waste and stormwater are released into adjacent waterways via built-in overflow conduits as a combined sewer overflow (CSO). The triggered overflow is necessary to avoid the flowback of untreated sewage into homes and streets (Barone et al., 2019; Burian et al., 1999; Connecticut Department of Energy and Environmental Protection, 2022).

In the modern day, the volume within a combined sewer system has several influencing factors: processing rate of the connected treatment facility, volume of domestic sewage, infiltration of water into pipes from groundwater, rain, or snowmelt, and inflow of stormwater from surface runoff (Zhang et al., 2018). Combined sewer overflows occur in more than 900 cities throughout the U.S., with many discharging directly into a coastal zone or its tributary (Eganhouse & Sherblom, 2001).

The threshold at which CSO events occur is difficult to forecast due to confounding influencing factors. However, total rainfall depth is the best measurement for establishing critical thresholds and predicting CSO events (Shroeder et al., 2011; Mailhot et al., 2014).

RELATIONSHIP BETWEEN CSO EVENTS AND NITROGEN LOADING IN SURFACE WATER

Combined sewer overflow events were historically accepted based on economic constraints to build combined sewer systems that could handle high volume flows during wet weather, as well as assumptions that the flushing time of the receiving water body was short, and wet-weather inflow of stormwater would dilute concentrations of pollutants (Barone et al., 2019; Burian et al., 1999). The idea that stormwater dilutes the concentration of pollutants carried by the wastewater within a combined system, therefore negating the negative impact on water quality should be reconsidered (Barone et al., 2019). The CSO is made up of stormwater runoff within the urban area as well as wastewater from all users within the wastewater treatment service area. Both the storm and wastewater carry their nutrient load from various sources, causing their effect on surface water to be amplified (Barone et al., 2019).

Combined sewer overflows contribute to nutrient pollution in surface waters from wastewater and stormwater sources. Stormwater carries concentrations of accumulated nutrients from non-point sources within the watershed and contains nutrients like nitrogen, with organic nitrogen as the dominant species. Nitrogen aggregates via roof and road runoff from inputs like atmospheric deposition from the burning of fossil fuels, pet waste, fertilizers, automotive detergents, and vegetative detritus such as leaf fall and yard clippings (Jani et al., 2020; Ma et al., 2021). Accumulation of wastewater over the entire sewer network from homes and businesses assembles pollutants and nitrogen from sources such as food, soaps, detergents, and human waste which contains pharmaceuticals as well as dissolved organic nitrogen and ammonia (JJ Environmental, LLC, 2015; USEPA, 2023).

Storm and wastewater in a combined system under normal volume moves within the sewer network to the local wastewater treatment plant, where processing occurs to remove organic matter and nutrients. Organic nitrogen and ammonia present in the influent get reduced during the primary and secondary treatment stages. During primary treatment, the influent flow moves through screens to remove large objects such as leaves, grass clippings, and trash. Next, the flow goes through a series of settling ponds or tanks to remove additional portions of the organic solid waste by taking advantage of density differences (Tibbetts, 2005). During secondary treatment, the remaining wastewater from primary treatment is “activated” by introducing microorganisms and oxygen, converting the suspended organic waste to ammonia via decomposition and then to nitrate through the process of nitrification (Lovett, 2020) (Fig. 5). However, as previously stated, during high flow volumes exceeding the capacity of the sewer system, the combined storm and wastewater is diverted directly to local waterways (CSO) thus bypassing treatment to reduce organic nitrogen and ammonia concentrations. The management of stormwater and CSOs is a critical component in reducing eutrophication in Long Island Sound and restoring its function and services to the region, as these discharges elevate levels of ammonia and total nitrogen in receiving waters (Barone et al., 2019; Eganhouse & Sherblom, 2001; Suchowska-Kisielewicz & Nowogóński, 2021; Wang, 2014).

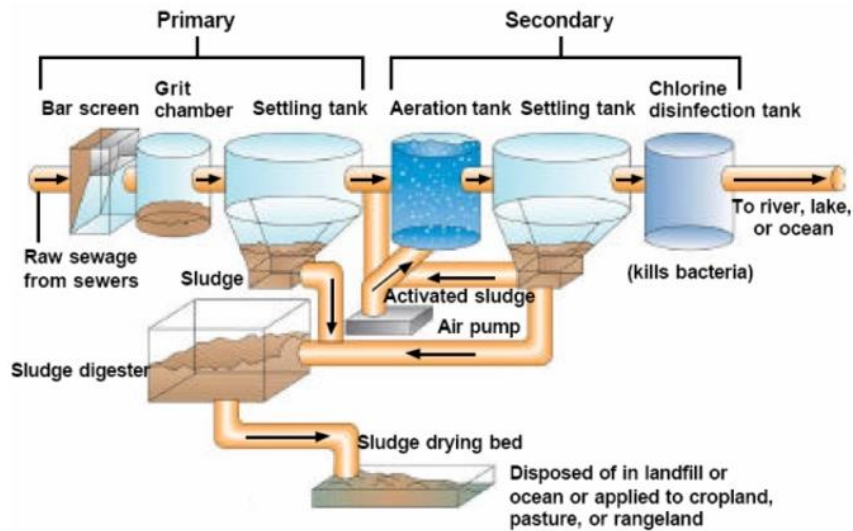


Figure 5. Wastewater Treatment Process. Graphic model showing the two standard phases of wastewater treatment. The primary phase consists of physical separation with screening and settling. Bacterial colonies added to the aeration tank in the secondary phase decompose remaining suspended organic solids in the partially clarified water and nitrifying bacteria convert ammonia to nitrate. (Queens University, 2004)

SYNERGISTIC EFFECTS OF CLIMATE CHANGE ON NITROGEN POLLUTION

Increased frequency of extreme precipitation and intense tropical storms resulting from anthropogenic climate change (Huang et al., 2021; Martel et al., 2021; Tabari, 2020) could exacerbate established nitrogen pollution issues with stormwater runoff and combined sewer overflows (Nie et al., 2019). Warming air temperatures cause more evaporation and more water vapor in the atmosphere. The Clausius–Clapeyron scale predicts that for every 1°C of warming, there will be an approximate 7 % increase in water vapor saturation in the atmosphere. This relationship is expected to heighten the severity of short-duration extreme rainfall (Martel et al., 2021) and increase the frequency of extreme precipitation events (Huang et al., 2021). Existing stormwater and combined sewage infrastructure designed under historic population and precipitation conditions, coupled with impervious surfaces, could cause more urban surface runoff and larger volumes of stormwater and CSO discharges (Alamdari et al., 2022). Climate change has a positive linear effect on combined sewer system overflows in urban areas as elevated storm intensity causes an increase in the percentage of pipes that fail to meet the higher volume demand (Nie et al., 2019). Expected larger discharge volumes per CSO event from climate change will increase pollutants discharged. Extreme short-duration rainfall will cause discharges of higher total nitrogen concentrations as built-up sources within the drainage area and sewage pipes are flushed out (Suchowska-Kisielewicz & Nowogoński, 2021; Salerno et al., 2018; Barone et al., 2019; Wu & Malmström, 2015; Alamdari et al., 2022).

CASE STUDY: EFFECT OF URBAN LAND COVER AND RAINFALL ON CSO EVENTS IN CONNECTICUT

The elevated volume of stormwater runoff correlates with the amount and extent of impervious surfaces within a watershed. Stormwater inflow into combined sewer systems can cause overflow events by elevating the volume past system capacity. I wanted to see how these factors correlate in selected Connecticut districts with combined sewer systems and documented CSO events.

Methods:

I chose four urban districts in Connecticut with a history of CSOs for study: Bridgeport, New Haven, Norwich, and Metropolitan Hartford (West Hartford, Hartford, East Hartford) (Figs. 6 & 7). I chose the months of March through September as they correlate with warmer weather and algae blooms in Long Island Sound. I also chose the parameter years 2016-2021 due to the scope of public access records for CSO events within the Connecticut wastewater management districts.

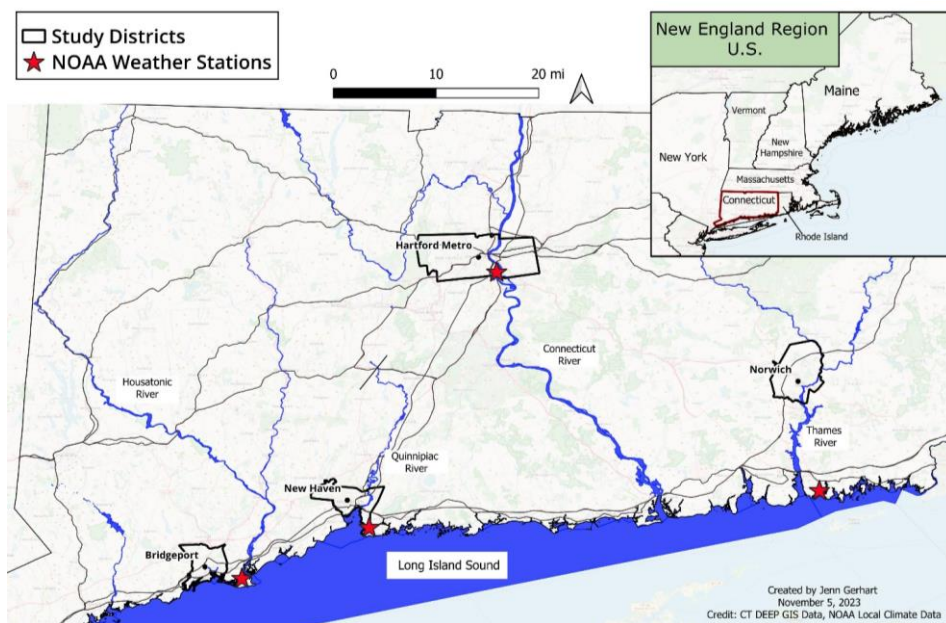


Figure 6. Study districts within the state of Connecticut. The map shows Connecticut's position within the New England region, the location and area of study districts, and the location of NOAA weather stations. (Connecticut Department of Energy and Environmental Protection, 2023; NOAA National Centers for Environmental Information, 2023)

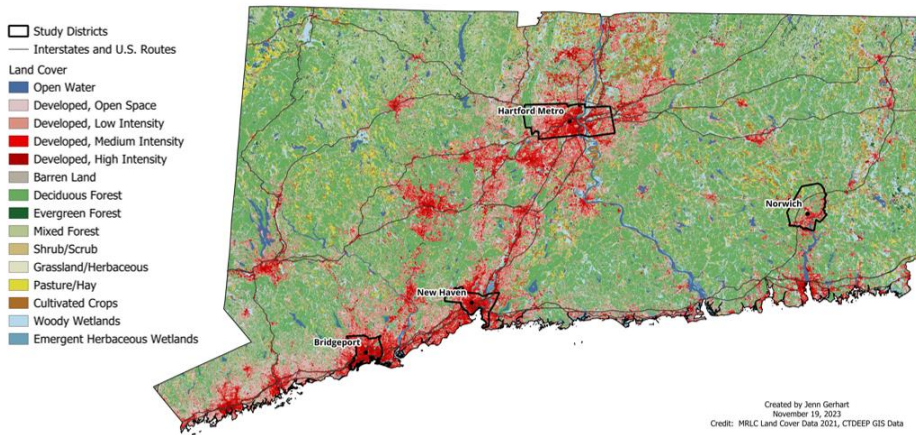


Figure 7. Land cover in the state of Connecticut. The map reflects 2021 land cover types throughout the state along with the location and area of study districts. (Multi-Resolution Land Characteristics Consortium, 2023; Connecticut Department of Energy and Environmental Protection, 2023)

I chose a historic baseline (1961 to 1991) and subsequent 30-year period (1992 to 2022) for the study months to look at changes in precipitation within the state. I aggregated the mean precipitation (in) by month and then calculated the change in the mean and percentage change for the two 30-year periods (NOAA National Centers for Environmental Information, 2023). Next, the total daily rainfall (in) and average daily precipitation (in) for each study district and year were calculated using local climatological data from NOAA weather stations (GHCND: USW00014752, WBAN: 14758, WBAN: 94702, WBAN: 14707) located within or near each district (NOAA National Centers for Environmental Information, 2023). Then I queried storm event data from the National Centers for Environmental Information (NCEI) using the following parameters: study months, period, floods, flash foods, heavy rain, tropical storms, and

hurricanes. I separated the returned data and aggregated it by year and study district or respective county.

I used the land and impervious cover data from the Multi-Resolution Land Characteristics and Consortium (MRLC) for the years 2016 and 2021 to calculate the percentage of urban cover and mean level of imperviousness within each study district. I also used the land cover data to segregate the percent of the urban cover into the levels of intensity: open ≤ 20 % imperviousness, light 21 to 49 % imperviousness, medium 50 to 79 % imperviousness, and high 80 to 100 % imperviousness (Multi-Resolution Land Characteristics Consortium, 2023). I created maps of Connecticut and studied districts with their land and impervious surface cover using the program QGIS.

The combined sewer overflow data for each district (Connecticut Department of Energy and Environmental Protection, 2023) I aggregated by month (March through September) for the available years between 2016 and 2021. To understand whether precipitation determines CSO volume, I calculated and plotted the median volume estimate range (gal) for each district against the total daily rainfall (in) for each corresponding year in a time series graph. I found no clear correlation between the median volume estimates (gal) and the total daily rainfall (in). This lack of correlation was likely due to the large variations within some of the volume estimate ranges, lack of recorded volume estimates, estimates being recorded as greater than a base value, or too many recorded estimates using the same value range. I then analyzed the CSO data using a different approach; the regulators triggered during a CSO event were tallied across all reporting years along with the corresponding total daily rainfall (in). Lastly, I performed a log transformation of the number of CSO triggers and then created a linear regression model with the

transformed data and the total daily rainfall (in) to analyze their correlation using the program R. I did not perform a linear regression analysis for Metropolitan Hartford and New Haven as their CSO volume estimates and regulator groupings did not allow for adequate differentiation of the data.

Results and Discussions:

All months March through September had a positive percentage increase in rainfall from 1961 to 2022 (Table 1), except May, which had a negative 13.39 % change. Between the two 30-year periods June, July, and September had positive percentage changes of 15.34 %, 10.90 %, and 16.41 %, respectively. The average precipitation per month (March-September) from 1992 to 2022 was 4.15 inches, an average increase of 0.17 inches per month from the reference period (1961to1991). In 2021, six storm events were reported where flooding or flash floods occurred due to extreme precipitation by localized or tropical storms. By contrast, between 2017 and 2020, eight total flood or flash flood events were reported (NOAA National Centers for Environmental Information, 2023). The districts of Bridgeport, Metropolitan Hartford, and New Haven were repeatedly affected by the extreme precipitation and flood events whereas Norwich was affected by only three of the events (all occurred in 2021), two of which were tropical storms.

The findings in the precipitation analysis are consistent with studies conducted on observed and predicted precipitation trends in Connecticut and New England (The Connecticut Institute for Resilience and Climate Adaptation (CIRCA) at UConn, 2019; Picard et al., 2022) for which the average precipitation for spring and summer months (March-August) were 4.02 and 4.04 inches for the reference periods of 1970 to 1999 and 1976 to 2005,

respectively. Furthermore, these studies predict either no change or an increase in total precipitation for spring through summer with an average monthly precipitation increase between 0.38 inches by midcentury (2040 to 2069) (The Connecticut Institute for Resilience and Climate Adaptation (CIRCA) at UConn, 2019) and 0.52 inches by late century (2070 to 2099) (Picard et.al, 2022). The outlier in the precipitation analysis is the negative change in monthly precipitation for May which goes against predicted outcomes. However, this difference could be attributed to the two severe and extreme droughts Connecticut experienced during May 2002 and 2012 from droughts that could have occurred between 1992 and 1999 (NOAA National Integrated Drought Information System, 2023).

Table 1. Precipitation Data for Connecticut. The table shows the mean precipitation (in) for the months of March-September for two 30-year periods 1961 to 1991 and 1992 to 2022, the change in mean precipitation (in) between the two periods, and the mean percentage change between the two periods. The table also shows flood events caused by extreme precipitation within the study districts for the months of March-September from 2017 to 2021.

Precipitation	March	April	May	June	July	Aug	Sept	
Mean (in) 1961-1991	3.94	4.14	4.33	3.78	3.76	3.97	3.9	
Mean (in) 1991-2022	4.05	4.18	3.75	4.36	4.17	4.01	4.54	
Δ Mean (in)	0.11	0.04	-0.58	0.58	0.41	0.04	0.64	
Mean % Change	2.79%	0.97%	-13.39%	15.34%	10.90%	1.01%	16.41%	
Flood Events Due to Extreme Precipitation	March	April	May	June	July	Aug	Sept	Total Events Per Year
2017				1				1
2018		1					1	2
2019					2	1		3
2020					1	1		2
2021					2	2	2	6

Bridgeport had the highest percentage of their district area as developed (92.76%, 2021) (Table 4) (Fig. 10), followed by New Haven (83.95%, 2021) (Table 3) (Fig. 9), Metropolitan Hartford (79.40%, 2021) (Table 2) (Fig.8), and Norwich (42.99%, 2021) (Table 5) (Fig. 11).

Between 2016 and 2021, established areas of developed land cover in the four districts shifted slightly as the mean percentage of open and light intensity development decreased (-0.18 %) while the mean percentage of medium and heavy intensity development increased (0.20 %). There was an average gain of 0.02 % for developed cover in all districts between 2016 and 2021, with an average increase in mean imperviousness from 42.32 % to 42.52 %.

Fourteen total flood events were reported within the study districts between 2017-2021 (NOAA National Centers for Environmental Information, 2023). Of those 14 events, Metropolitan Hartford was affected by 10: 2017(1), 2018(1), 2019(2), 2020(2), 2021(4); New Haven by five: 2018(1), 2019(1), 2020(1), 2021(2); Bridgeport by four: 2018(1), 2020(2), 2021(1); Norwich by three: 2021(3). The increase in the extent of impervious surfaces and rainfall is a likely driver of increased flood events within the study districts. This correlation is consistent with other studies in that rainfall-induced flooding in urban areas relates to a high degree of impervious cover, combined sewer systems, and stormwater drains that get blocked with debris from surface runoff (Agonafir et al., 2023; Prokić et al., 2019; Russo et al., 2021).

Precipitation and the number of triggered CSO regulators in Bridgeport were positively correlated ($r = 0.56$, $p\text{-value} < 0.0001$) (Fig. 12). In contrast, this relationship was weaker for Norwich ($r = 0.25$, $p\text{-value} = 0.0108$) (Fig. 13). Consequently, precipitation can explain 56% of the variation in CSO events for Bridgeport, yet only 25% of the variation in CSO events for Norwich, which suggests that precipitation has a larger effect size on CSO events in Bridgeport. I expected precipitation would have a greater effect on CSOs in Bridgeport due to the higher impervious cover but was not expecting Norwich to have so many CSO occurrences nor the number of occurrences when the corresponding precipitation was zero. The rate of CSO

occurrences in Norwich was 100 out of 642 days with recorded precipitation (March to Sept., 2019 to 2021) (Table 6) and in Bridgeport 68 out of 1,162 days with recorded precipitation (July to Sept., 2016; March to Sept., 2017 to 2021) (Table 7), although Norwich has a lower ratio of estimated median volume (gal) release per event (14,450.52 (gal) per occurrence) compared to Bridgeport (129,845.70 (gal) per occurrence).

Precipitation, being a stronger explanatory variable for the CSO occurrences in Bridgeport could be accounted for by the location of the rainfall data used in the study. The NOAA weather station for Bridgeport was closer to the district boundary, making the data more reliable than the data used for Norwich. Another difference in the regression outcomes could be the extent of impervious surfaces in Bridgeport around the areas that have a combined sewer system. Bridgeport's district is over 90 % developed, and its areas of highest imperviousness seem to be concentrated in the combined sewer areas, meaning that precipitation accumulation and surface runoff are likely drivers of CSO events. Norwich has a much lower extent of both developed area and level of imperviousness which limits the contribution of stormwater inflow to the CS system, but despite the lack of impervious surfaces, there was a higher frequency of total CSO events and those occurring when corresponding precipitation is zero compared to Bridgeport. This contradiction between impervious surface extent and coverage, rainfall, and CSO events suggests the inaccuracy of rainfall data notwithstanding, potential driving factors for CSO events in Norwich could be areas of sewer infrastructure that cannot accommodate the current user volume and potential groundwater infiltration into the sewer system.

To improve understanding of the relationship between precipitation, stormwater runoff, and CSO volumes in the combined sewer areas, I suggest a more comprehensive analysis of

rainfall measurements, urban cover, and impervious data. One approach is to take rainfall measurements at different spatial scales within the districts in addition to analyzing the impervious areas directly connected to the CSS (Sohn et al., 2020). This approach will provide more reliable data and correlation between these factors.

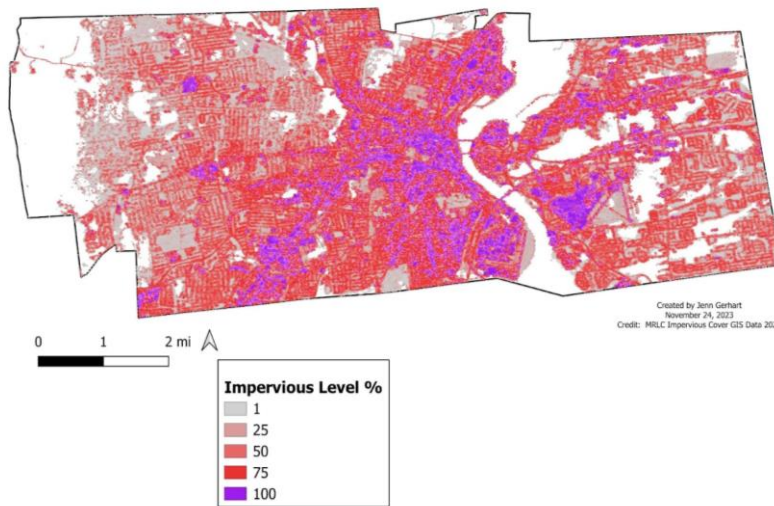


Figure 8. A map of Metropolitan Hartford, CT, and the impervious level of developed land cover in 2021. Map includes the cities of East Hartford, Hartford, and West Hartford.

Table 2. Developed land cover change in Hartford, CT between 2016 and 2021.

Developed Land Cover		2016	2021	Δ (2021-2016)
% of Area		79.39 %	79.40 %	0.01 %
	Imperviousness			
Open Space	≤ 20 %	17.10 %	16.81 %	-0.29 %
Light Intensity	21 to 49 %	20.13 %	19.96 %	-0.17 %
Medium Intensity	50 to 79 %	29.72 %	29.99 %	0.27 %
High Intensity	80 to 100 %	12.45 %	12.64 %	0.19 %
Mean Imperviousness of Developed Area		38.65 %	38.93 %	0.28 %
MRLC Land Cover and Urban Impervious GIS Data 2016 & 2021 Calculated using QGIS				

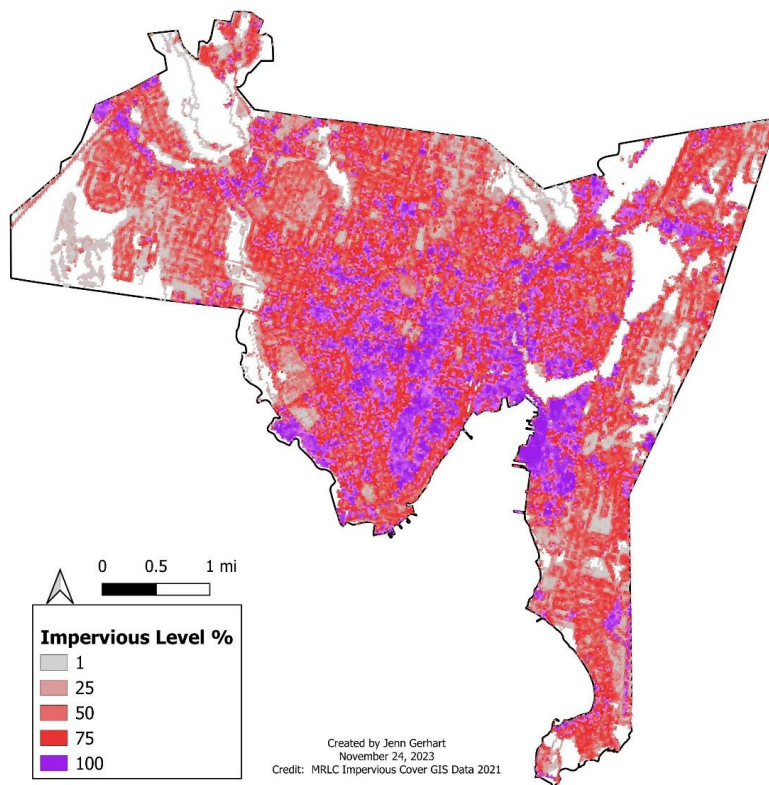


Figure 9. A map of New Haven, CT, and the impervious level of developed land cover in 2021.

Table 3. Developed land cover change in New Haven, CT between 2016 and 2021.

Developed Land Cover		2016	2021	Δ (2021-2016)
% of Area		83.95 %	83.95 %	0 %
Imperviousness				
Open Space	≤ 20 %	10.38 %	10.29 %	-0.09 %
Light Intensity	21 to 49 %	16.31 %	16.16 %	-0.15 %
Medium Intensity	50 to 79 %	35.99 %	36.15 %	0.16 %
High Intensity	80 to 100 %	21.28 %	21.42 %	0.14 %
Mean Imperviousness of Developed Area		49.37 %	49.54 %	0.17 %
MRLC Land Cover and Urban Impervious GIS Data 2016 & 2021 Calculated using QGIS				

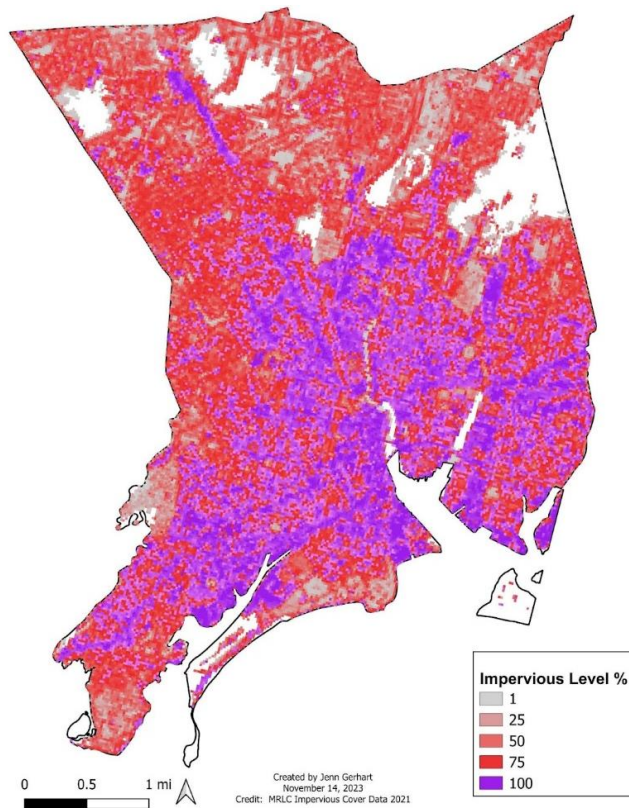


Figure 10. A map of Bridgeport, CT, and the impervious level of developed land cover in 2021.

Table 4. Developed land cover change in Bridgeport, CT between 2016 and 2021.

Developed Land Cover		2016	2021	Δ (2021-2016)
% of Area		92.97 %	92.76 %	0.04 %
Imperviousness				
Open Space	≤ 20 %	5.96 %	5.74 %	-0.22 %
Light Intensity	21 to 49 %	12.08 %	11.94 %	-0.14 %
Medium Intensity	50 to 79 %	39.21 %	39.41 %	0.20 %
High Intensity	80 to 100 %	35.48 %	35.66 %	0.18 %
Mean Imperviousness of Developed Area		63.12 %	63.36 %	0.24 %
MRLC Land Cover and Urban Impervious GIS Data 2016 & 2021 Calculated using QGIS				

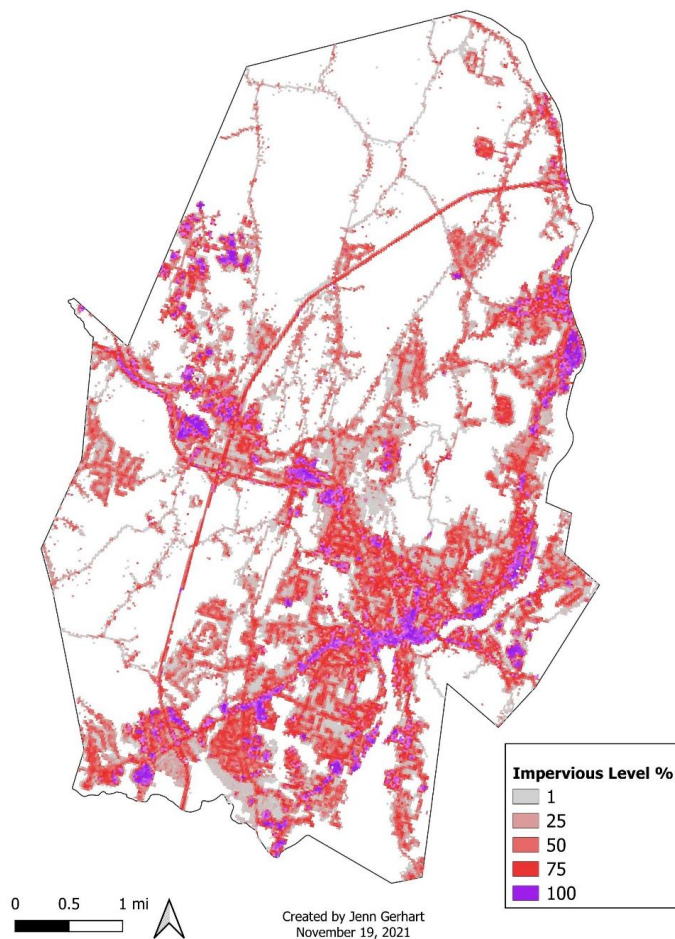


Figure 11. A map of Norwich, CT, and the impervious level of developed land cover in 2021.

Table 5. Developed land cover change in Norwich, CT between 2016 and 2021.

Developed Land Cover		2016	2021	Δ (2021-2016)
% of Area		42.96 %	42.99 %	0.03 %
Imperviousness				
Open Space	≤ 20 %	12.22 %	12.13 %	-0.09 %
Light Intensity	21 to 49 %	12.29 %	12.28 %	-0.01 %
Medium Intensity	50 to 79 %	13.89 %	13.98 %	0.09 %
High Intensity	80 to 100 %	4.55 %	4.59 %	0.04 %
Mean Imperviousness of Developed Area		18.14 %	18.23 %	0.09 %
MRLC Land Cover and Urban Impervious GIS Data 2016 & 2021 Calculated using QGIS				

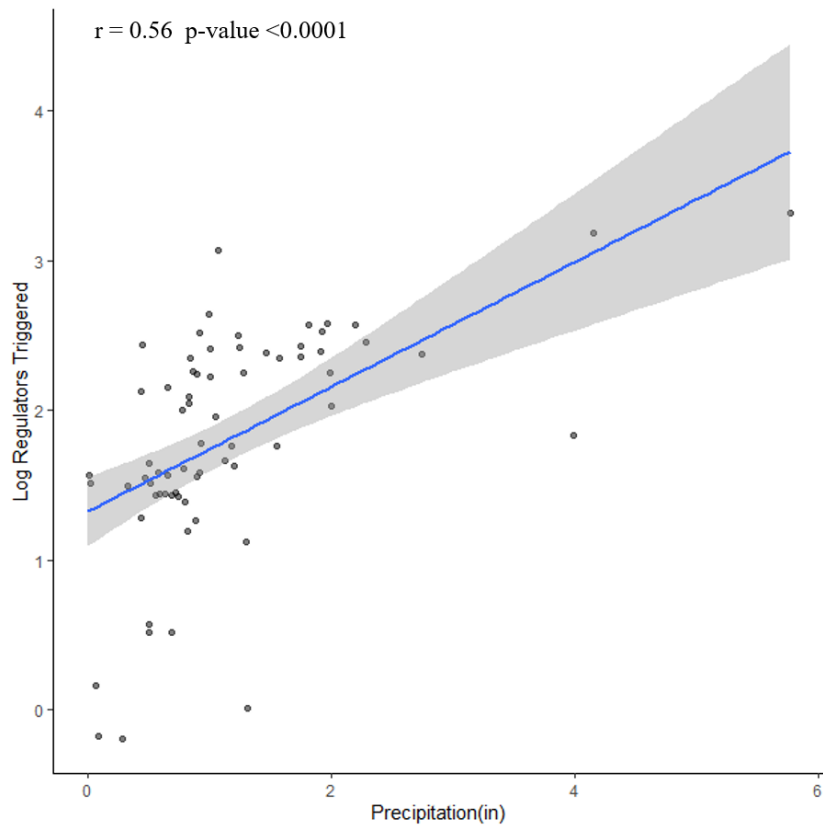


Figure 12. Linear regression of the number of regulators triggered (log-transformed) and the corresponding precipitation (in) for CSO events in Bridgeport, CT.

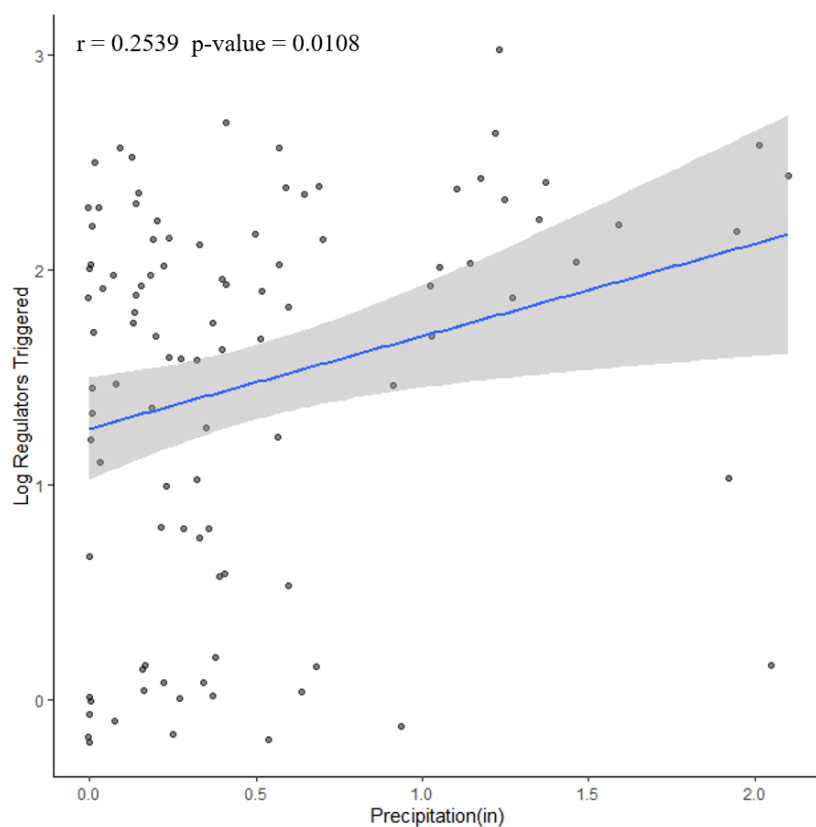


Figure 13. Linear regression of the number of regulators triggered (log-transformed) and the corresponding precipitation (in) for CSO events in Norwich, CT.

Table 6. CSO occurrences and precipitation in Norwich, CT.

March-September	Total Days with CSO Occurrences	% of Days with CSO Occurrences	Average Median Volume Estimate (gal)	Average Daily Precipitation (in) Groton New London Airport
2019	26	10.75%	549,201	0.14
2020	37	17.29%	351,597	0.08
2021	37	17.76%	544,255	0.11

Table 7. CSO occurrences and precipitation in Bridgeport, CT.

March-September	Total Days with CSO Occurrences	% of Days with CSO Occurrences	Avg. Median Volume Estimate (gal)	Avg. Daily Precipitation (in) Sikorsky Memorial Airport, CT
2016 (July-September)	6	6.52%	1,569,667	0.12
2017	10	4.67%	787,506	0.12
2018	15	7.01%	1,640,000	0.15
2019	14	6.54%	923,932	0.14
2020	10	4.21%	447,778	0.12
2021	13	5.61%	3,460,625	0.15

Conclusion:

The precise relationship between rainfall, CSO events, and nitrogen pollution within the Connecticut districts was difficult to assess due to a lack of historic public CSO data, available locations for rainfall data, and unavailable sources of continuous nitrogen monitoring to directly examine the CSO events and subsequent nitrogen discharge. Despite the data limitations, elements of established factors and their relationship to CSO events appear in the analysis. Three of the four study districts have a high percentage of urban cover coupled with a high level of imperviousness and increased total average precipitation. Linear regression analysis provided some evidence of the influence of these relational factors on CSO events. Rainfall had a moderate influence ($r = 0.56$) on CSO events for Bridgeport which could be attributed to the high degree of urban cover ($> 92\%$ of the district area) and level of imperviousness within the district area (mean level $> 63\%$).

Long-term design plans to decrease the effects of CSO discharges within the Connecticut districts include the decoupling of combined sewers in specific sections of Metropolitan Hartford, New Haven, and Norwich (Connecticut Department of Energy and Environmental

Protection, 2023). The proposed construction in New Haven of bioswales around a CSO-prone area is expected to reduce the inflow of stormwater in that section of the city (Connecticut Department of Energy and Environmental Protection, 2023). Plans have been drafted to build CSO retention storage and increase the capacity of targeted wastewater treatment plants in all CSO districts in phases over the next fifteen to twenty years (Connecticut Department of Energy and Environmental Protection, 2023). These implementations will restrict nitrogen entering rivers and estuaries via CSO discharges, however, nitrogen pollution within these urban districts will still need to be addressed as the predicted increases in precipitation (Picard et al., 2023) and extreme rainfall events (Huang et al., 2021) on impervious surfaces continue to produce nutrient pollution from stormwater runoff (Alamdari et al., 2022; Ma et al., 2021).

EFFECTS OF PHARMACEUTICALS AND PERSONAL CARE PRODUCTS (PPCPs) ON BIOLOGICAL NUTRIENT REMOVAL PROCESSES IN WASTEWATER

Biological Nutrient Removal Process in Wastewater Treatment

As the global population increases and more people live in urbanized areas, the demand for PPCPs grows (Richmond et al., 2017). There are potentially many environmental threats from chemical compounds found in PPCPs; those of particular concern are antibiotics and antimicrobials found in many household products. These compounds have the potential to change the abundance and composition of bacterial communities that perform specific functions necessary to reduce nutrient pollution to surface waters (Chen et al., 2017; Li et al., 2019; Lopez et al., 2021). Most wastewater treatment plants use bacterial assemblages during the secondary treatment phase (Fig. 5) to decompose suspended organic waste and reduce ammonia through the nitrification process (Environmental Protection Agency, 2016). Moreover, it is becoming more common for wastewater treatment to include an additional biological process in the secondary phase to reduce nitrate through the microbial denitrification process (Environmental Protection Agency, 2016).

Wastewater treatment plants that utilize activated sludge for nutrient removal during secondary treatment mineralize organic nitrogen into nitrate through the decomposition of organic waste and oxidation of ammonia during the process of nitrification (Lovett, 2020). Shifts in the dominant form of nitrogen in wastewater from ammonia to nitrate benefits surface water by reducing the harmful effects of ammonia toxicity on aquatic organisms, however, the nitrate produced during this process contributes to eutrophication of surface water (Hornung, 1999). Nitrate is a driver in eutrophication, algae growth, and harmful algae blooms (HABs) in

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nitrogen-limited ecosystems such as estuaries and estuarine wetlands (Hornung, 1999). Harmful algae blooms can smother coral, clog the gills of fish, reduce dissolved oxygen in the water when the algae decompose, change the composition of aquatic plant communities, and produce toxins that can be fatal to fish, mammals, and birds and cause illness in humans (National Oceanic and Atmospheric Administration, 2016; Connecticut Department of Energy and Environmental Protection, 2019). A significant factor in the eutrophication, subsequent HABs, and hypoxic conditions in Long Island Sound is nitrate concentrations in wastewater effluent (Connecticut Department of Environmental Protection, 2000).

The direct response to nitrate pollution by wastewater treatment effluent in the Long Island Sound watershed has been to add biological nitrogen removal (BNR) retrofits to wastewater facilities. Biological nitrogen retrofits work by adding an additional biological process to the secondary treatment phase. The retrofits, added in sequence to the aerobic nitrification process, reduce produced nitrate via microbial anaerobic denitrification (JJ Environmental, Inc., 2015) (Fig. 14). Simplified, the retrofit is an anoxic tank activated with facultative anaerobic bacteria that use nitrate to oxidize organic carbon resulting in the production of nitrogen gas thus reducing nitrate concentrations in effluent (Chapin et al., 2012).

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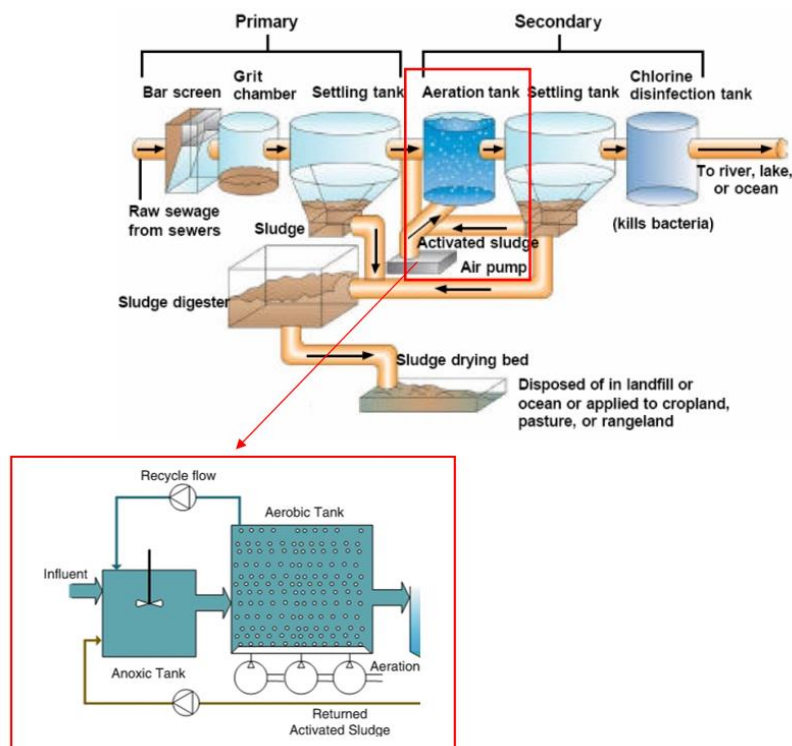


Figure 14. Biological nitrate removal retrofit and placement within the wastewater treatment process. The graphic inset (red) shows the anoxic tank which would be activated with denitrifying bacteria and added in line with the aerobic (aeration) tank which would be activated with nitrifying bacteria. The graphic inset (red) also shows the two tanks have an internal recycled flow mechanism to provide decomposition of suspended organic solids, ammonia reduction (aerobic/aeration tank), and nitrate reduction (anoxic tank). Treatment Process Graphic (Queens University, 2004) Inset Graphic (Fig. 2 in Banayan et al., 2019)

Effects of PPCPs on Bacterial Colonies in Biological Nitrate Removal

The efficacy of biological nitrogen removal in wastewater treatment processing could be hindered by pharmaceuticals and personal care products in wastewater. Commonly prescribed pharmaceuticals found in wastewater influent, like the antihistamine Diphenhydramine and the

antidepressant Fluoxetine, suppressed denitrification rates in artificial stream sediments (Robson et al., 2020). Prescribed antibiotics and antimicrobials in personal care products are another threat to the bacterial processes of nitrification and denitrification used in nitrogen removal of wastewater. Common antibiotics in wastewater treatment effluent in the U.S. include ciprofloxacin, ofloxacin, and sulfamethoxazole (Kostich et al., 2014). These three antibiotics can decrease the rate of denitrification of microbial assemblages in wastewater, streams, or groundwater (Li et al., 2019; Lopez et al., 2021; Robson et al., 2020; Underwood et al., 2011; Wang et al., 2017). Over-the-counter antimicrobial compounds like Triclosan, a ubiquitous antimicrobial found in household and personal care products such as hand sanitizers, soaps, toothpaste, and fabrics are commonly found in wastewater. Triclosan is known to decrease nitrifying cultures and rates of nitrification in wastewater treatment and denitrification in soil samples (Bodle, 2016; Chen et al., 2019; Lopez et al., 2021; Tan et al., 2021).

Overall, antibiotics and antimicrobial compounds alter microbial metabolic processes resulting in slower growth rates, leading to a shift in bacterial communities in which the abundance of nitrogen-reducing species is diminished (Chen et al., 2017; Li et al., 2019; Robson et al., 2020; Tan et al., 2021; Wang et al., 2017; Xie et al., 2022). Therefore, it is reasonable to expect that as the demand for PPCPs increase, the concentration of the ecological disrupting compounds in wastewater will also increase (Richmond et al., 2017). Subsequently, these compounds at higher concentrations could diminish the effective removal of nitrogen from wastewater through biological treatment.

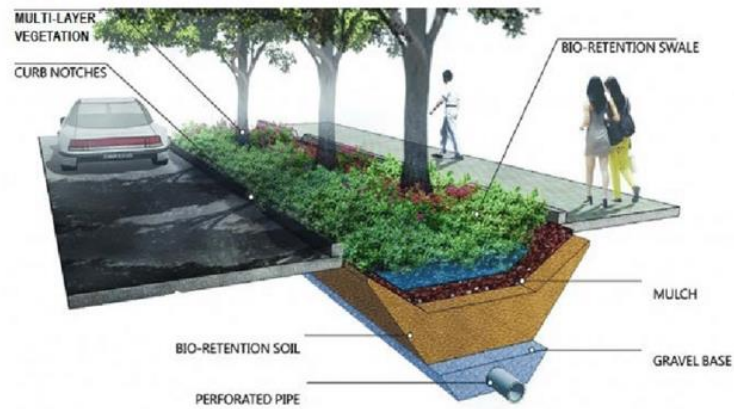
SUGGESTIONS FOR REDUCTION AND MONITORING

More than half the nitrogen loading to Long Island Sound can be attributed to human activities such as atmospheric deposition, fertilizer, and wastewater effluent (Tetra Tech, Inc., 2020; Connecticut Department of Environmental Protection, 2000). In urban areas, atmospheric deposition and fertilizer use contribute nitrogen via stormwater and CSO outflows. There is a lack of continuous nitrogen data available for point sources such as stormwater and CSO outflows in Connecticut. To get a better understanding of the impact of nitrogen from stormwater and CSO discharges and their correlation with rainfall, rainfall data within the urban watershed as well as continuous nitrogen data from stormwater and CSO outfalls should be obtained using rain gauges and nitrogen sensors. Within medium to high-density impervious areas, rain gauges should be strategically placed to obtain accurate information on precipitation patterns. Lowell, MA has implemented strategic placement of rain gauges throughout its urban area and uses this information to make decisions about flow rate and releases through its wastewater treatment facility to mitigate nitrogen loads to local streams (City of Lowell, 2018). Continuous nitrogen data could be gathered at surface water outflows for stormwater and combined sewer systems using new technology like the Stony Brook Nitrogen Sensor® which can measure ammonia and nitrate simultaneously within a stream flow (Verify Global, 2021). A sensor of this type could be used to accurately correlate the contribution of nitrogen in surface water to stormwater and CSO discharges.

Current undeveloped and open spaces within urban districts should be preserved and future urban development should meet low-impact design requirements to keep the area of urban cover and level of impervious surfaces minimal. Integrating green infrastructure, such as

bioswales, porous pavement, and green roofs, as a part of low-impact development can lower surface runoff by intercepting and dispersing precipitation. Current highly urbanized areas could retrofit green infrastructure at different spatial levels and for different surface types to reduce volumes of surface runoff. By lowering surface runoff, the number of CSO events, the magnitude of nitrogen pollution to rivers and estuaries, and damage caused by flooding will also be reduced. Green infrastructure lowers the amount of stormwater runoff, peak flows in adjacent streams, and flooding in urban areas by providing areas of interception at different scales. Rainfall intercepted by green infrastructure is dispersed through different pathways such as infiltration, evapotranspiration, and temporary storage (Li et al., 2019; Rajashekar, 2020; Roseboro et al., 2021; Torres et al., 2022) (Figs. 15 & 16).

a.



b.

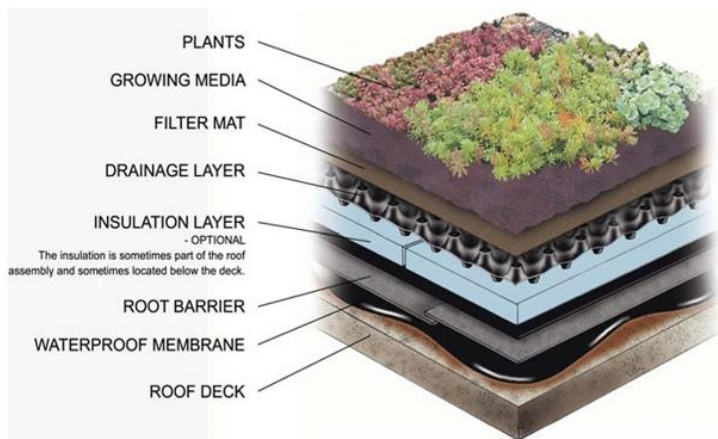


Figure 15. Examples of green infrastructure designs. Conceptual models of the basic designs for (a.) bioswales and (b.) green roofs. These green infrastructure types use a vegetative layer for interception, infiltration, and evapotranspiration as well as a soil layer for percolation and temporary storage. a.(Fig. 1 in Dinic-Brankovic et al., 2019)) b.(American Hydrotech, Inc., 2023)

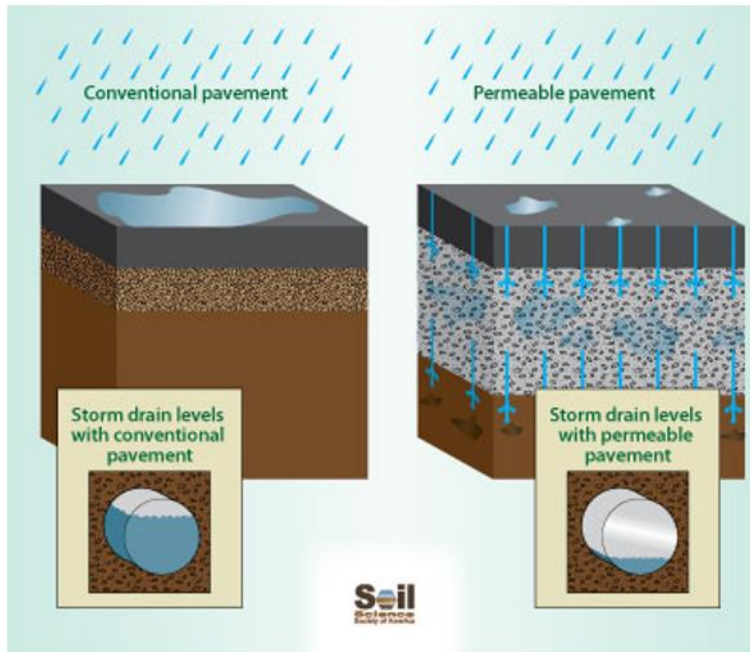


Figure 16. Porous (permeable) pavement. The conceptual model shows the infiltration, percolation, and temporary storage capacity of porous (permeable) paving compared to conventional paving. (Soil Science Society of America, 2018)

A modeling study using porous pavement to retrofit all the parking lots within the city of Buffalo, NY is a good example of how green infrastructure alleviates stormwater runoff issues (Roseboro et al., 2021; Torres et al., 2022). Porous pavement retrofits could decrease future CSO volumes by 2 to 31 % accounting for future extreme precipitation perpetuated by climate change (Roseboro et al., 2021). When integrating multiple green infrastructure practices, like bioswales, porous pavement, and green roofs within the same areas, the heightened infiltration and dispersion of precipitation results in a higher percentage of reduced runoff and flooding (Li et al., 2019; Rajashekar, 2020; Salerno et al., 2018). An example of this integrated reduction impact is

a simulation study for Illinois where porous pavement and rain gardens were used in parking lots and reduced major flooding by 35 to 55 % (Li et al., 2019).

Areas with the highest levels of imperviousness, the greatest risk of flooding, and CSO events can be specifically targeted for green infrastructure retrofits. Investments in multi-strategy retrofits for the districts of metropolitan Hartford, Bridgeport, and New Haven could help meet the state's goal of reducing future nitrogen pollution to surface waters from nonpoint sources (Connecticut Department of Energy and Environmental Protection, 2019). Decreasing the volume of surface runoff should lead not only to fewer CSO events but also reduced wash-off of built-up nitrogen from impervious surfaces (Alamdari et al., 2022), lessening the nitrogen contribution of stormwater runoff directly to surface water or through CSO events.

To determine if pharmaceuticals are harming nitrogen removal rates, a testing program could be started for common antibiotics and personal care compounds that have been established to decrease both nitrification and denitrification processes. Having baseline data for these compounds could provide a tool for evaluating occurrences of depressed nitrogen reduction efficiency happening under otherwise normal parameters.

CONCLUSION

Eutrophication from nutrient pollution, such as nitrogen, diminishes ecosystem functions in affected aquatic systems. Many estuary systems along U.S. coasts and inland lakes such as the Great Lakes experience harmful algae blooms and hypoxic conditions resulting from anthropogenic eutrophication. Efforts to reduce nitrogen pollution include targeting point sources such as wastewater effluent using biological nitrification and denitrification capabilities. When pollutants from point sources, such as combined sewer and stormwater discharges, originate from non-point sources, the management of the pollutants is difficult to address. My research suggests that precipitation influences CSO events but mainly through stormwater inflow. Consequently, stormwater is controlled by the extent of precipitation and impervious cover. Nitrogen mitigation efforts with a holistic approach that accounts for all influencing parameters within the watershed will have the greatest impact. For example, low-impact development combined with green infrastructure retrofit can greatly reduce surface runoff and flooding in urban areas (Li et al., 2019; Pappalardo et al., 2017; Maragno et al., 2018). If these strategies were combined with denitrification capabilities and increased capacity of CSO storage and wastewater treatment volumes, CSO events could be eliminated, and total nitrogen loads from stormwater minimized. More research is needed using direct measurements of nitrogen loads from CSO and stormwater discharges and rainfall to better understand the relationship between these parameters and their contribution to surface water. Furthermore, assessments should be conducted on wastewater influent from plants participating in nitrogen mitigation to ascertain current concentrations of PPCPs and the efficacy of biological processes. Measured concentrations of PPCPs in wastewater influent can be used to analyze negative impacts on the

nitrification (ammonia reduction) and denitrification (nitrate reduction) processes during wastewater treatment.

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