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Higher incidence of novel coronavirus (COVID-19) cases in areas with combined sewer systems, heavy precipitation, and high percentages of impervious surfaces

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ABSTRACT

Combined sewer systems (CSS) are water management systems that collect and transport stormwater and sewer water in the same pipes. During large storm events, stormwater runoff may exceed the capacity of the system and lead to combined sewer overflows (CSOs), where untreated sewer and stormwater are released into the environment. Though current literature reveals inconclusive evidence regarding the infectivity of SARS-CoV-2 in wastewater, detection of infectious SARS-CoV-2 in urine and feces of COVID-19 patients led to concerns that areas contaminated by CSOs may be a reservoir of SARS-CoV-2 and may result in illness after the ingestion and/or inhalation of contaminated splashes, droplets, or aerosols. We investigated the association between COVID-19 incidence and CSSs and whether this association differed by precipitation and percent imperviousness as a proxy for possible CSOs. We fitted a quasi-Poisson regression model to estimate the change in percentage of incidence rate of COVID-19 cases in counties with a CSS compared to those without, adjusting for potential confounders (i.e., state, population density, date of first documented COVID-19 case, social vulnerability, and percent vaccinated) and including interaction variables between CSS, precipitation, and impervious surfaces. Our findings suggest that heavy precipitation in combination with high percentages of imperviousness is associated with higher incidences of COVID-19 cases compared to non-CSO counties (p-value = 2.5e-9). For example, CSS-counties with precipitation of 10 in/month may observe a higher incidence in COVID-19 cases compared to non-CSO counties if their impervious surfaces exceed 33.5% [95%CI: 23.0%, 60.0%]. We theorize that more COVID-19 cases may be seen in counties with a CSS, heavy precipitation, and high percentages of impervious surfaces because of the possible increase in frequency and severity of CSOs. The results suggest links between climate change, urbanization, and COVID-19.

Keywords: COVID-19, Combined sewer system (CSS), Combined sewer overflow (CSO), Precipitation, Impervious surfaces

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1. Introduction

Combined sewer systems (CSS), water management systems that collect and transport stormwater and sewer water in the same pipes to be treated at a wastewater treatment plant, are used by over 750 cities in the United States (Tibbetts, 2005; U.S. EPA, 2004). These systems are often outdated and may not be designed to support the trend of increasing installation of impervious surfaces that result in high peak flow rates of stormwater runoff. During large storm events, high volumes of stormwater runoff quickly flow into the pipes and may exceed their capacity resulting in a combined sewer overflow (CSO), where untreated or barely treated sewer water mixed with stormwater is released into the environment (U.S. EPA, 2004, 2015a). The United States Environmental Protection Agency (EPA) estimates that 950 billion gallons of untreated sewer and stormwater released into the environment are caused by sewer overflows annually (Tibbetts, 2005; U.S. EPA, 2004).

Previous studies have revealed high concentrations of SARS-CoV-2 RNA in sewage and wastewater (Barrios et al., 2021; Peccia et al., 2020; Sherchan et al., 2020) and SARS-CoV-2 has been detected to be viable for hours to several days in various types of water, including wastewater (Carducci et al., 2020). However, the presence of SARS-CoV-2 RNA in wastewater may not accurately represent the infectious virus due to the difference in decay times (Bivins et al., 2020; de Oliveira et al., 2021; Sala-Comorera et al., 2021). While no known study has revealed the infectivity of SARS-CoV-2 virus in sewage or wastewater, studies have suggested the possible infectivity of SARS-CoV-2 virus in urine and feces collected from COVID-19 patients, including those who are asymptomatic (Jeong et al., 2020; Sun et al., 2020; Xiao et al., 2020). The inconclusive evidence regarding the infectivity of SARS-CoV-2 in wastewater, but frequent detection of infectious SARS-CoV-2 in the urine and feces of COVID-19 patients and high concentrations of SARS-CoV-2 RNA in untreated wastewater, reveal the need for further research in order to identify and understand possible links between untreated wastewater and COVID-19 (Ahmed et al., 2021). Though transmission of the virus through wastewater has not been verified, if untreated wastewater is a potential mechanism of exposure, infectivity from combined sewage may occur from ingestion of accidental contaminated water, contact with contaminated surfaces, or inhalation of splashes, droplets, or aerosols (Cahill and Morris, 2020; Han and He, 2021; Heller et al., 2020). The authors of a recent preliminary analysis studying the relationship between flood events and spikes of COVID-19 cases in seven areas with CSSs suggests a potential link between spikes in COVID-19 cases after flood events in areas with CSSs, but noted that their findings were preliminary and inconclusive (Han and He, 2021). The authors of that article urge for more studies that further examine CSSs as a potential risk factor of COVID-19 (Han and He, 2021).

We investigated the association between COVID-19 incidence and CSS and whether the association was modifiable by precipitation and percent of impervious surfaces as a proxy for possible CSOs.

2. Methods

2.1. Data acquisition and processing

Our study period included all 18 months from February 2020 to July 2021. County boundaries and land area were obtained from the US Census Bureau.

We obtained data on daily COVID-19 cases and total population in United States counties from February 1, 2020 to July 31, 2021, from USA Facts and total monthly precipitation (inches) in continental United States counties from February 2020 to July 2021 from the National Oceanic and Atmospheric Administration (NOAA). The daily percentages of the population that acquired complete doses of vaccinations in United States counties were obtained from the Centers for Disease Control and Prevention (CDC). Daily COVID-19 cases and vaccination data were aggregated to monthly data to match the monthly total precipitation data. Counties that did not have precipitation data were omitted from the analysis. There were multiple counties whose total vaccination percentage by July 31, 2021 was reported as 0%. CDC records indicate that these were likely missing data rather than true values and were therefore removed from the analysis.

The locations of the cities that use CSSs were obtained from EPA. There are 228 cities that use a CSS in our study. CSS was used as a binary variable: (1) represents counties that have at least one city that uses a CSS and (0) represents counties that do not have any cities that use a CSS. As CSS was treated as a binary variable, wastewater and stormwater in counties that had at least one city with a CSS may also include cities that are manage by other types of stormwater and sewage systems, such as municipal separate storm and sewer systems and septic tanks. The counties that do not have a city that manages their wastewater and stormwater using a CSS manage their wastewater and stormwater using systems other than a CSS.

The number of counties in each category is shown in Table 1 and the number of cities that use a CSS within the CSS-counties is shown in the supplementary files (Fig. S1).

The 2013 urban-rural classifications were acquired from the CDC’s National Center for Health Statistics. Counties with urbanicity classifications 1–4 (metropolitan areas) were used for this analysis. Non-metropolitan areas were not used in this analysis due to the differences in rural vs. urban areas other than CSSs. For example, stormwater runoff management is a common issue in metropolitan areas because of the higher percentage of impervious surfaces compared to in rural areas (U.S. EPA, 2015b). Also, metropolitan areas have a much higher prevalence of CSSs compared to non-metropolitan areas. The distribution of urbanicity classifications among counties with and without a CSS is shown in the supplementary files (Fig. S2).

The percent impervious surfaces for each county were calculated from the 2019 Multi-Resolution Land Characteristics (MRLC) Consortium’s National Land Cover Database (NLCD).

Social vulnerability of each United States county was represented by the CDC’s 2018 Social Vulnerability Index (SVI), which uses 15 social factors within the four themes: socio-economic status, household composition and disability, minority status and language, and housing type and transportation access, to calculate an overall SVI value. SVI values are between 0 and 1 and values closer to 1 signify higher social vulnerability.

2.2. Statistical analysis

We fitted a quasi-Poisson regression model, shown in Eq. (1), to estimate the change in percentage of incidence rate of COVID-19 cases in counties with a CSS compared to counties without. We adjusted for

Table 1
Descriptive statistics of counties with and without CSS.

|                                      | CSS (standard deviation) | Non-CSS (standard deviation) |
|--------------------------------------|--------------------------|-----------------------------|
| Number of counties (n)               | 228                      | 837                         |
| Average population count             | 351,813                  | 198,160                     |
| (493,821)                            | (484,161)                |                             |
| Average population density (persons/km²) | (2018.8)                | (772.8)                     |
| Average cumulative COVID-19 cases per 100,000 Persons | 9978                  | 10,226                      |
| (as of July 31, 2021)                | (2258)                   | (2869)                      |
| Average vaccination percentage (%)   | 46.2                     | 36.6                        |
| (as of July 31, 2021)                | (12.2)                   | (14.2)                      |
| Average monthly precipitation (inches) | 3.57                    | 3.91                        |
| (as of July 31, 2021)                | (0.83)                   | (1.54)                      |
| Average percent impervious surfaces (%) | 9.60                   | 4.85                        |
| (as of July 31, 2021)                | (10.9)                   | (6.97)                      |
| Average SVI                          | 0.43                     | 0.45                        |
| (as of July 31, 2021)                | (0.23)                   | (0.28)                      |
confounders: State, population density, date of first case, SVI, and percent of the population that was vaccinated (hereafter referred to as vaccination percentage) (Eq. (1)).

Interaction terms between CSS, precipitation and impervious surfaces were used (Eq. (1)) as approximate proxies to represent CSO occurrences due to lack of CSO data. These values for counties with a CSS are appropriate approximate stand-ins to represent CSO occurrences because of the previously established associations between precipitation, impervious surface, and CSOs (Salerno et al., 2018; Tibbetts, 2005; U.S. EPA, 2004). As precipitation increase and permeable surfaces decrease, the higher volume and speed of stormwater runoff that flows into the CSS may increase the likelihood and severity of a CSO occurrence (Salerno et al., 2018; Tibbetts, 2005; U.S. EPA, 2004).

$$\log(\text{Incidence}) = \log(\text{Rate}) = \beta_0 + \beta_1 \text{CSS} + \beta_2 \text{Precip} + \beta_3 \text{Imperv} + \beta_4 \text{SVI} + \beta_5 \text{Month} + \beta_6 \text{Year}$$

where $Y_{c, m, t}$ represents new COVID-19 cases for county $c$ during month $m$, year $t$. $\gamma_c$ represents the total population of county $c$. $State_c$ represents the state in which county $c$ is located. $PopDen_c$ represents the population density accounting for land area of county $c$. $FirstCase_c$ represents the days since the first COVID-19 case was recorded in county $c$. $Vacc_c$ represents the percentage of the population that has completed their COVID-19 vaccinations in county $c$ during month $m$, year $t$. $SVI_c$ is the Social Vulnerability Index of county $c$. $Month_c$ is a categorical variable that represents the month. $Year_t$ represents an indicator for year 2020 or 2021. $CSSBinary_c$ is a binary variable of 1 if county $c$ has a CSS or 0 otherwise. $Precip_c$ represents the total precipitation for county $c$ during month $m$, year $t$. $Imperv_c$ represents the percentage of impervious cover in county $c$. $\beta_1, 2, ... 14$ are regression coefficients estimates.

3. Results

3.1. Descriptive statistics

The average population size, percentage of the population that is fully vaccinated for COVID-19, and percentage of impervious surfaces is higher in counties with a CSS compared to counties without (Table 1). However, the average monthly precipitation and cumulative case rate is approximately the same in counties with and without a CSS (Table 1). The cumulative number of COVID-19 cases in CSS and non-CSS counties with precipitation and impervious surface percentages in the upper quartile can be found in the supplementary files (Fig. S3).

3.2. COVID-19 cases, and interactions between CSS, precipitation, and impervious surfaces

Fig. 1 shows the relationship between the incidence rate of COVID-19 cases and the presence of a CSS in a county. The figure also reveals how this relationship changes at varying levels of percent impervious and total monthly precipitation. The y-axis indicates percent difference in the incidence rate of COVID-19 between counties with a CSS and counties without a CSS. The x-axis indicates percent impervious and the lines of different colors ranging from yellow to red indicate a varying level of total monthly precipitation. No precipitation is represented by the light-yellow line in Fig. 1. As the precipitation increases up towards 10 in./month, the line colors progress towards red. As an illustration of interpretation, please see the reddest line, which represents 10 in/month of precipitation, where the x-axis reaches 80% impervious surface. This point indicates that a county with 10 in/month of precipitation, 80% imperviousness, and a CSS had 133.1% [95%CI: 23.5%, 340.3%] higher incidence rate of COVID-19 cases than counties with the same level of precipitation and imperviousness, but with no CSS.

Fig. 1 reveals that the incidence rate of COVID-19 in counties with a CSS compared to without is roughly similar under conditions of low precipitation (yellow). However, when monthly precipitation is high (red), as the percentage of impervious surfaces increases, we observed a significant increase in the incidence rate of COVID-19 cases in counties with a CSS compared to without a CSS (Fig. 1). For example, CSS-counties with high levels of precipitation, such as 10 in/month, may observe a significantly higher incidence rate of COVID-19 cases compared to non-CSO counties if their percentage of impervious surfaces exceed 33.5% [95%CI: 23.0%, 60.8%]. Therefore, heavy precipitation in combination with impervious surfaces is associated with an increase in incidence rate of COVID-19 cases in counties with a CSS compared to in counties without ($\beta_{14} = +2.7e-3, p-value = 2.5e-9$) (Fig. 1).

The coefficient of interaction between the binary CSS variable, precipitation, and impervious surface percentage ($\beta_{14}$) stratified by population density is shown in the supplementary files (Table S1).

4. Discussion

Our main findings suggest that heavy precipitation in combination with high percentages of impervious surfaces in counties with a CSS is associated with a higher incidence rate of monthly COVID-19 cases. We theorize that more COVID-19 cases may be seen in counties with a CSS, heavy precipitation, and high percentages of impervious surfaces because of the possible increase in frequency and severity of CSOs. This study suggests that COVID-19 may be impacted by climate change and urbanization. An increase in severity of precipitation from storm events due to climate change (U.S. EPA, 2016) as well as the increase in impervious surfaces as the world is increasingly urbanized (U.S. EPA, 2015b), are likely to contribute to the frequency and severity of CSO occurrences (Tibbetts, 2005), and therefore, possibly, the number of COVID-19 cases.

A limitation of this research includes the lack of detailed CSO data. Though we hypothesize that in areas with a CSS, heavy precipitation in combination with high percentage of imperviousness may contribute to higher rates of COVID-19 cases due to CSOs, we do not have the CSO data to make this conclusion. Although previous literature linked CSOs to impermeable surfaces and high precipitation, future research is needed to explore our results. This research need is consistent with calls from previous literature (Han and He, 2021) that CSO data indicating dates, frequency, and/or volume, would be an important addition to research. Another limitation with our study, similar to other place-based studies, includes the likelihood of inter-county travel of residents such as residents that commute to
work in a different county than their place of residence. These residents may as a result be exposed to conditions in both counties, although analysis only considers their place of residence.

This work makes an assumption regarding the infectivity of SARS-CoV-2 in untreated wastewater, which has been made by multiple scholars studying this underdeveloped field of research (Bilal et al., 2020; Elsamadony et al., 2021; Han and He, 2021; Olusola-Makinde and Reuben, 2020; Shutler et al., 2021). However, though SARS-CoV-2 RNA has been frequently detected in wastewater at high concentrations (Barrios et al., 2021; Peccia et al., 2020; Sherchan et al., 2020), the presence of RNA may be an ineffective indicator of infectivity because of its slower decay in wastewater compared to the infectious virus (Bivins et al., 2020; de Oliveira et al., 2021; Sala-Comorera et al., 2020). The presence of RNA may be an ineffective indicator of infectivity because of its slower decay in wastewater compared to the infectious virus (Bivins et al., 2020; de Oliveira et al., 2021; Sala-Comorera et al., 2020). Additionally, the reported occurrence of transmission of COVID-19 from infectious wastewater is rare (Ahmed et al., 2021). However, conclusions could not be made due to limited sample sizes of recent research about this topic (Ahmed et al., 2021). Given the frequent detection of infectious SARS-CoV-2 in feces and urine collected from COVID-19 patients (Jeong et al., 2020; Sun et al., 2020; Xiao et al., 2020), we postulate that the transmission of COVID-19, especially from recently collected raw wastewater, is possible. Additional studies about the infectivity of SARS-CoV-2 as well as possible transmission routes from untreated wastewater are needed before we can definitively conclude whether there is a connection between CSOs/untreated wastewaters and COVID-19 cases (Ahmed et al., 2021).

Previous studies and policy guidelines suggest increased infectivity of COVID-19 indoors (Nwanaji-Enwerem et al., 2020). Since CSOs occur outdoors and we have adjusted for potential confounders such as population density, future studies are needed to help further explain our findings and the mechanisms through which CSOs may impact COVID-19 cases. We also suggest further analysis at higher spatial resolution to study factors such as differences in associations among socio-demographic groups that may be obscured at the county-level.

5. Conclusions

Our findings reveal that heavy precipitation in combination with high percentages of imperviousness is associated with a higher incidence rate of COVID-19 cases in counties with a CSS compared to in counties without a CSS. The results suggest implications for COVID-19 in relation to CSOs, which are linked to climate change and urbanization.

CRediT authorship contribution statement

Alisha Yee Chan: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Data Curation, Writing-Original Draft, Visualization. Honghyok Kim: Methodology, Software, Validation, Writing - Review & Editing, Visualization. Michelle L. Bell: Writing - Review & Editing, Supervision, Project Administration, Funding Acquisition.

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.

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Appendix A. Supplementary data
Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.153227.