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A Review of Combined Sewer Overflows and Gastrointestinal Illness in a Changing Climate

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Abstract

Purpose of Review During a combined sewer overflow (CSO) event, the capacity of a sewer system is exceeded, and untreated sewage, wastewater, and stormwater are released into nearby water bodies. CSOs occur in urban areas due to heavy precipitation, which is expected to occur more frequently and at higher intensity in certain regions of the world due to increasing climate variability. After a CSO, humans can be exposed to pathogens through recreational activities and contaminated drinking water. While previous research has quantified the impacts of CSOs on water quality indicator species and described the effects of CSOs on coastal wetland ecosystems, there is limited research on the potential human health impacts of CSOs. We conducted a literature search of peer-reviewed epidemiological studies that investigated associations between CSOs and human health outcomes.

Recent Findings Our literature search and screening methods returned eight studies on the association between CSOs and gastrointestinal (GI) illness in Europe and North America. Our selected peer-reviewed publications included five different study designs: time series, case-crossover, retrospective cohort, case-control, and case time series, with study periods including years 2002 to 2019.

Summary The included studies showed evidence of a positive association between CSOs and GI illness, and one study suggested that sewer infrastructure improvements may decrease the burden of GI illness in future decades.

Keywords Combined sewer overflow · Gastrointestinal illness · Wastewater infrastructure · Extreme precipitation

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Introduction

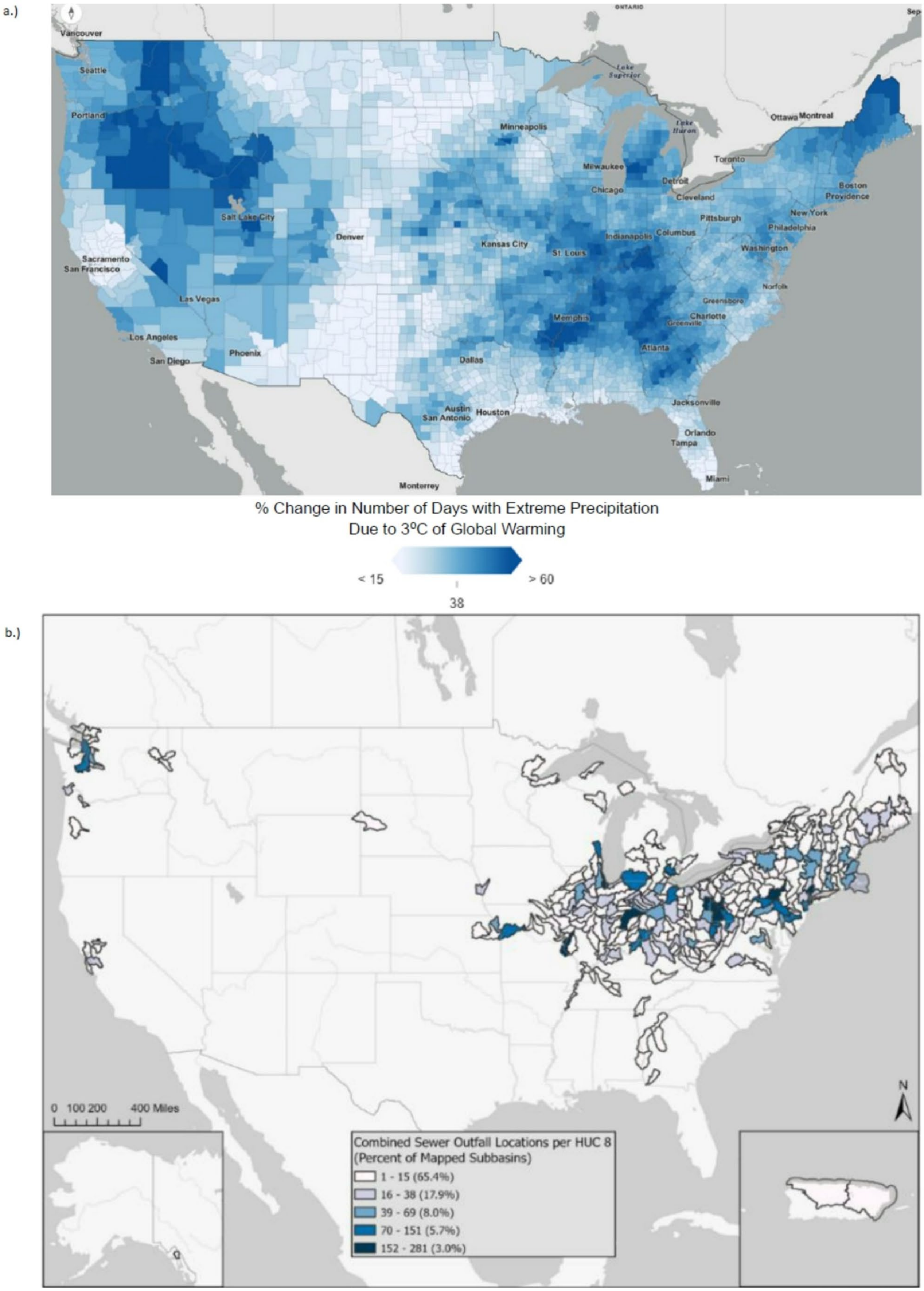
The relationship between heavy rainfall and gastrointestinal (GI) illness has been well-studied in regions with modern wastewater treatment and infrastructure. In Canada, rainfall events greater than the 93rd percentile increased the odds of a waterborne disease outbreak by a factor of 2.283, 95% CI: (1.216, 4.285) based on data from 1975 to 2001 [1], and a study in the United States (US) found a strong association between disease outbreaks from contaminated surface water and extreme precipitation during the month of the outbreak from 1948 to 1994 [2]. In England and Wales, an analysis of waterborne disease outbreaks from 1910 to 1999 showed a significant association between excess cumulative rainfall in the past week and outbreak occurrence [3]. However, a review of 24 studies that evaluated an association between extreme precipitation or temperature and waterborne disease, with most study sites located in Asia or North America, reported heterogeneous results across studies, and therefore, recommended further research into effect measure modifiers, such as etiologic agent, geographic region, season, type of water supply, water source, or water treatment [4].

Combined sewer overflow (CSO) events are likely to be an important mediator of the association between rainfall and waterborne disease because they are common and significant sources of sewage-associated pathogens. Previous research suggested that ten times more sewage was present in a receiving waterbody when a CSO event occurred synchronously with a heavy rain event, than when a heavy rain event occurred in the absence of a CSO event [5]. Combined sewer systems (CSSs) transport both wastewater and stormwater to wastewater treatment plants in the same pipe, and if the capacity of the system is exceeded, they are designed to release untreated sewage, wastewater, and stormwater directly into nearby water bodies at designated outfall locations [6, 7]. The capacity of CSSs varies by system, and thus the amount of rainfall that can cause CSO events varies by system as well. For example, in the Milwaukee River Basin (Wisconsin, US), greater than three inches of rainfall in 24 h may overwhelm CSSs and cause CSOs [8]. While CSOs are most frequently caused by heavy precipitation, snowmelt can also contribute to runoff and overwhelm system capacity [9, 10]. Many of the CSSs in North America were built from the 1850s through the 1940s in older urban centers, such as Chicago, IL, New York, NY, Philadelphia, PA, Boston, MA, and Toronto (Ontario, Canada) [7, 11]; the CSSs in England were built even earlier, many during the nineteenth century [12]. CSSs are expensive to renovate or replace, and efforts to reduce CSOs often include multi-million or multi-billion dollar infrastructure improvement plans that span across multiple decades [11, 13, 14]. In 2004, the US Environmental Protection Agency (EPA) documented CSO control expenditures in 48 communities adding to more than $6 billion [7]. More recently, the cost of CSO correction in the US was estimated to be $36.5 billion [15].

Fig. 1 Projected Changes in Days with Extreme Precipitation and Current Watersheds with Permitted Combined Sewer Outfall Locations. (**a**) Projected percent changes in days with extreme precipitation per year due to a global average temperature increase of 3 °C since pre-industrial levels from the 5th National Climate Assessment, "*Change in Days with Extreme Precipitation"* attributed to U.S. Global Change Research Program, NOAA, CICS-NC, Esri licensed under CC BY 4.0 [20] (**b**) Locations of permitted combined sewer outfall locations [21], grouped spatially by watershed subbasins, Hydrologic Unit Code (HUC) 8. Combined sewer outfall locations per HUC 8 were binned according to the natural breaks classification method; a histogram showing the frequency of HUC 8 subbasins by the number of outfall locations is provided (Figure S1). Hawaii, not shown, did not have any permitted combined sewer outfall locations

Heavy rainfall events have likely increased in frequency, intensity, and/or amount of heavy precipitation on a continental-scale in Asia, Europe, and North America since 1950 [16]. Each of these three continents includes countries with one or more urban centers relying on CSSs [17]. In certain regions, "the projected increase in frequency and intensity of heavy precipitation (high confidence) will increase rain-generated local flooding (medium confidence)" [18], placing additional stress on CSSs. In the United States, the annual number of extreme precipitation days (precipitation totals in the top 1% of historical amounts) increased by approximately 60% in the Northeast and 45% in the Midwest from 1958 to 2021 [19]. By years 2081–2100, total warming from pre-industrial levels is projected to be approximately 2.7 °C, assuming an intermediate greenhouse gas emissions scenario. At 3 °C of global warming, the number of days per year with extreme precipitation is expected to increase in both the Northeast and the Midwest of the US, and these regions contain most of the 772 US municipalities that are served by CSSs (Fig. 1) [20–23].

Ninety million illnesses occur in the US each year due to surface water recreation events, at a cost of $2.2 - $3.7 billion annually [24]. In the region surrounding the Great Lakes, a major source of both drinking water and recreational activities for more than 40 million people, changing weather conditions are expected to increase the risk of waterborne disease [8]. Among 44 waterborne disease outbreaks from recreational exposures in 2003–2004, 45% of outbreaks were attributed to bacteria, 34% were attributed to parasites (mainly *Cryptosporidium*), 14% were attributed to viruses, and 7% were chemical- or toxin-mediated [25]. Discharge from a CSO can contain a variety of viral, protozoan, and bacterial pathogens that vary in concentration over space and time following a CSO event [10, 26, 27]. Viral pathogens, such as norovirus, tend to have short incubation times (12–48 h) [28, 29], bacterial incubation times vary depending on the specific pathogen, and protozoan


a.)
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Pittsburgh
Washington
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Indianapolis
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Kansas City
Denver
Salt Lake City
Sacramento
San Francisco
Las Vegas
Los Angeles
San Diego
Phoenix
Dallas
Memphis
Atlanta
Charlotte
Greensboro
Norfolk
Jacksonville
Orlando
Tampa
Miami
Austin
San Antonio
Houston
Monterrey
% Change in Number of Days with Extreme Precipitation
Due to 3°C of Global Warming
< 15
38
> 60
b.)
0 100 200 400 Miles
N
Combined Sewer Outfall Locations per HUC 8
(Percent of Mapped Subbasins)
1 - 15 (65.4%)
16 - 38 (17.9%)
39 - 69 (8.0%)
70 - 151 (5.7%)
152 - 281 (3.0%)

pathogens, such as *Cryptosporidium* or *Giardia* can have incubation times up to 12 or 25 days, respectively [30]. Common symptoms resulting from infection with waterborne biological pathogens include GI symptoms, such as vomiting and diarrhea [30]. Increased precipitation due to changing weather conditions is predicted to increase annual rates of cryptosporidiosis and giardiasis in metropolitan areas, such as Vancouver, Canada [31], but few studies have directly evaluated the relationship between CSO events and human health outcomes.

In addition to biological contaminants, discharge from CSO events can also contain pharmaceuticals, illicit drugs, heavy metals, and pesticides [32], and recent studies have suggested that some of these wastewater pollutants could have detrimental effects on cardiovascular [33] and neurological [34, 35] health in humans. Since a 2004 report to Congress, in which the US EPA described having "limited information on actual human health impacts" from CSO events [7], projections of increased extreme precipitation events in certain regions have placed further emphasis on the need for an updated synthesis of CSO-associated health impacts. To address this need, we conducted a scoping review of the peer-reviewed literature to evaluate existing evidence of associations between CSOs and gastrointestinal, cardiovascular, or neurological human health outcomes.

Materials and Methods

Identification of Relevant Search Terms and Databases

We identified search terms related to sewer overflow events and three categories of human health outcomes, including gastrointestinal, cardiovascular, and neurological effects (Table 1) [32–35]. Our search was conducted for peer-reviewed literature using PubMed and Web of Science databases, limited to English language, and run through March 18th 2025 with no start date limit; the protocol was registered with the International Prospective Register of Systematic Reviews (PROSPERO) [36], and full documentation of the search terms is provided in Table S1.

Screening and Data Extraction

We included studies that reported an estimate of the association between sewer overflow events and gastrointestinal, cardiovascular, or neurological human health outcomes. Articles that were quantitative but did not provide a measure of association, such as studies that only provided correlation statistics or *p*-values, were excluded. We did not exclude studies based on design or approach. Each abstract of the peer-reviewed articles identified from the literature search was screened by two reviewers on the team, using the web-based systematic review software, SWIFT-Active Screener (SWIFT-AS) [37]. Next, each article included after abstract-screening was reviewed in full by two members of the team through SWIFT-AS software. Review studies and predictive modelling articles that were relevant to our inclusion criteria were marked during the abstract screening process so that the references of these studies could be abstract screened and full-text screened if necessary. To facilitate comparisons across studies and focus on wastewater infrastructure that is designed to overflow under high flow conditions, we decided to only include articles that specifically assessed CSOs and secondary sewage bypass events occurring within CSSs, rather than sanitary sewer overflow and other sewage spillover events. Data, such as title, location, population, exposure, study design, outcome, and sample size were extracted from each included article by one team member, and then the extracted data were reviewed by a second team member for accuracy.

Table 1 Keywords for PubMed and Web of Science Literature Searches

Exposure	Health Outcome
extreme precipitation, extreme rainfall, high precipitation, sewer overflow, sewage overflow, overflowing water, persistent extreme precipitation, precipitation extremes, rainfall intensity, rainfall extremes	Gastrointestinal: diarrhea, vomiting, abdominal pain, gastrointestinal illness, ulcer, jaundice, liver disease, liver damage, hepatic toxicity, liver hemorrhaging, inflammatory bowel disease, ulcerative colitis
	Cardiovascular: cardiovascular disease, heart disease, hypertension, stroke, lipid dysregulation, cholesterol levels, pregnancy-induced hypertension, pre-eclampsia, hematological damage, cardiopulmonary mortality, ischemic heart disease, chronic heart disease, cerebrovascular disease, chronic rheumatic heart disease, myocardial infarction
	Neurological: central nervous system damage, muscle twitching, paresthesia, paralysis, vertigo, dizziness, headache, seizure, epilepsy, chronic neurologic effects, ALS[a], amyotrophic lateral sclerosis, Parkinson's disease, dementia, Alzheimer's, palsy, ataxia, neurological disorder

[a]ALS: amyotrophic lateral sclerosis

Narrative Summaries and Study Quality Evaluations

The main findings of each study were reported as narrative summaries, and study quality evaluation was conducted by at least two different reviewers for each included study. More information on the methods for study quality evaluation is available in supplementary material (See Supplementary Material, Study Quality Evaluation).

Results

Our literature search and screening process identified eight studies on associations between CSOs and gastrointestinal health outcomes, zero studies on CSOs and cardiovascular health outcomes, and zero studies on CSOs and neurological outcomes (Fig. 2; Table 2). The search terms returned 756 studies in May of 2022, and 263 additional studies in March of 2025, making a total of 1,019 studies (Fig. 2). One included study was identified by checking the references of papers that were marked as modelling or review studies (Fig. 2). Narrative summaries and study quality evaluations of included studies are presented in supplemental material (See Supplemental Material, Narrative Summaries, Study Quality Evaluation; Figure S2). The study locations included Wisconsin, Massachusetts, Ohio, and Georgia in the US, as well as cities in Denmark and Germany (Table 2; Fig. 3). Half of the studies were time series analyses of emergency department (ED) visits for GI illness, two studies used self-matched study designs with ED visits for GI illness, and two studies relied on questionnaire responses for outcome data (Table 2). Though proposed exposure routes varied, all eight studies presented evidence of positive associations between CSOs and GI illness (Fig. 3).

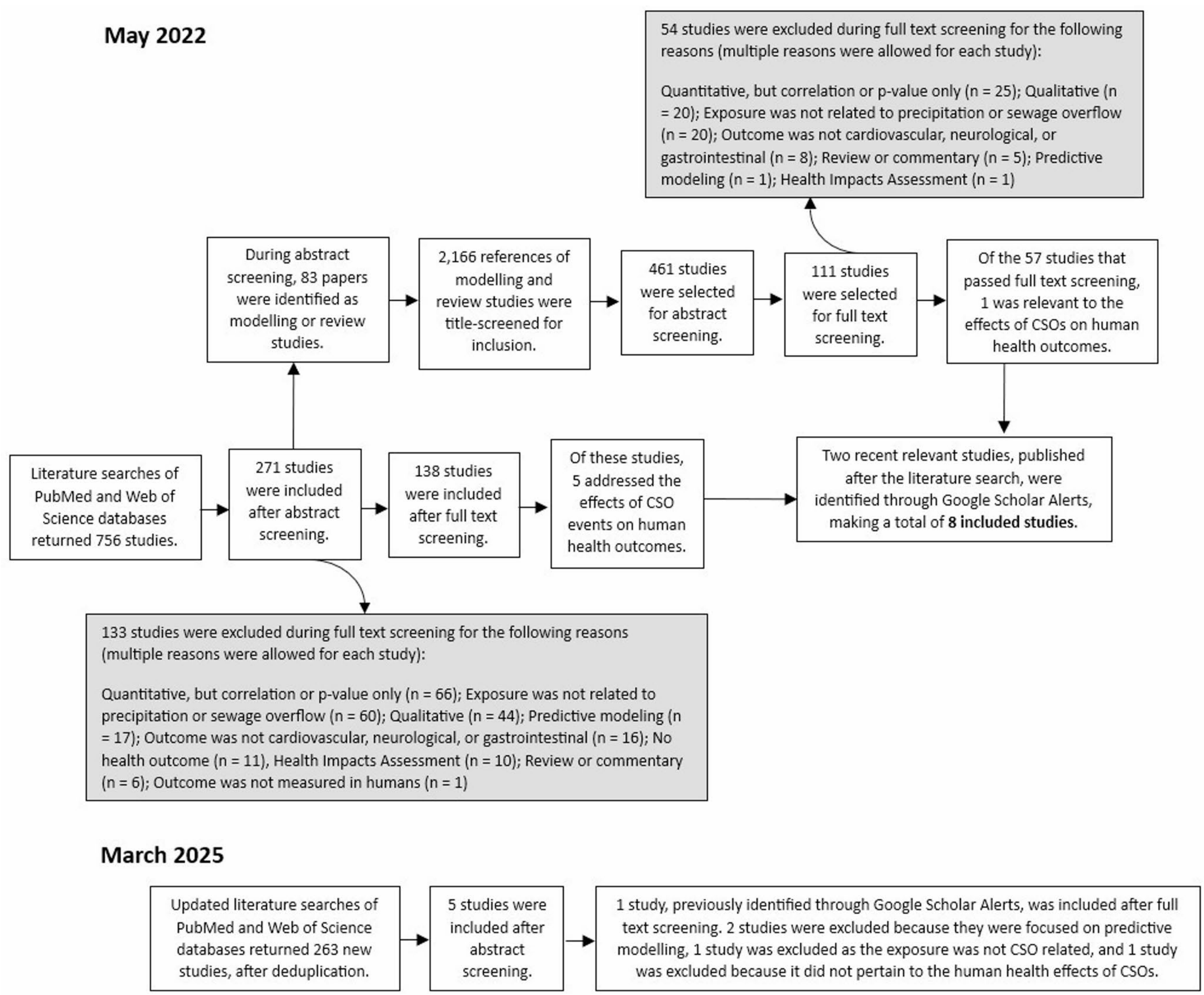

Fig. 2 Selection of Included Studies. (CSO: combined sewer overflow)

Table 2 Summary of Data from Included Studies

Title	Location	Population	Exposure	Study Design	Outcome & Sample Size
Pediatric Emergency Department Visits for Diarrheal Illness Increased After Release of Undertreated Sewage [38]	Milwaukee, Wisconsin, US[a]	Residents of the Milwaukee metropolitan area, ages 0–18 years	Secondary sewage-bypass events and rainfall; separate analyses for residents using a CSO[b]-impacted drinking water source and residents using other sources	Time series	Daily number of ED[c] visits for GI[d] illness (2002–2004) $n=1,096$ days
Association between Rainfall and Pediatric Emergency Department Visits for Acute Gastrointestinal Illness [39]	Milwaukee, Wisconsin, US	Residents of the Milwaukee metropolitan area, ages 0–18 years	Sewage release events and rainfall	Time series	Daily number of ED visits for GI illness (2002–2007) $n=2,191$ days
Gastrointestinal Illness among Triathletes Swimming in Non-polluted versus Polluted Seawater Affected by Heavy Rainfall, Denmark, 2010–2011 [40]	Copenhagen, Byen København, Denmark	Physically fit adults participating in the swimming segment of a triathlon competition	Participation in the swimming competition held on the 15th of August in 2010, when the swim course was contaminated by discharge from a CSO and bypasses from a wastewater treatment plant	Retrospective cohort	Reported symptoms of diarrhea or vomiting $n=1,769$ participants (838 from 2010; 931 from 2011)
Outbreak of *Cryptosporidium hominis* following river flooding in the city of Halle (Saale), Germany, August 2013 [41]	Halle, Saxony Anhalt, Germany	Kindergarten children who are residents of Halle	Visits to previously flooded areas	Case-control	Reported symptoms of gastroenteritis and stool tested positive for *Cryptosporidium hominis* $n=81$ (20 cases; 61 controls)
Extreme Precipitation and Emergency Room Visits for Gastrointestinal Illness in Areas with and without Combined Sewer Systems: An Analysis of Massachusetts Data, 2003–2007 [42]	Eastern Massachusetts, US	Residents of three study regions in eastern Massachusetts that vary by CSO presence and exposure route, all ages	Heavy (≥90th and ≥95th percentile) and extreme (≥99th percentile) precipitation events; separate analyses for a region exposed to CSOs recreationally, a region exposed to CSOs by drinking water, and a region with no CSOs	Time series	Daily number of ED visits for GI illness $n=1,826$ days
Combined sewer overflow events and childhood emergency department visits: A case-crossover study [43]	Cincinnati, Ohio, US	Residents of the City of Cincinnati, ages 0–18 years	Proximity to CSO effluent site, defined as having a residential address within 500 m of a combined sewer outfall location	Case-crossover	ED visits for GI illness at Cincinnati Children's Hospital Medical Center (2010–2014) $n=1,559$ ED visits
Combined Sewer Overflows and Gastrointestinal Illness in Atlanta, 2002–2013: Evaluating the Impact of Infrastructure Improvements [44]	Atlanta, Georgia, US	Residents of the City of Atlanta, all ages	CSO events of any volume, small CSO events (<25th percentile of volume), medium CSO events (≥25th percentile and <75th percentile), and large CSO events (≥75th percentile of volume)	Time series	Daily number of ED visits for GI illness $n=3,907$ days
Association between combined sewer overflow events and gastrointestinal illness in Massachusetts municipalities with and without river-sourced drinking water, 2014–2019 [45]	Northern Massachusetts, US	Residents of the 17 Massachusetts municipalities that border the Merrimack River, all ages	CSO events categorized as <90th, ≥90th, ≥95th, and ≥99th percentile of discharge volumes	Case time series	ED visits for acute GI illness from all hospitals in Massachusetts (January of 2014 through September of 2019) $n=100,206$ ED visits

[a]US: United States, [b]CSO: combined sewer overflow, [c]ED: emergency department, [d]GI: gastrointestinal

Outcomes

Most of the studies included in this review, except for two outbreak investigations [40, 41], relied on ED visit data to measure an adverse GI health outcome (Table 2). It is likely that measures of association reported by studies of ED visits were closer to the null than the associations reported by outbreak investigations because the ED visit studies did not include non-emergent and self-limiting cases of GI illness (Fig. 3). Both outbreak investigations used questionnaires

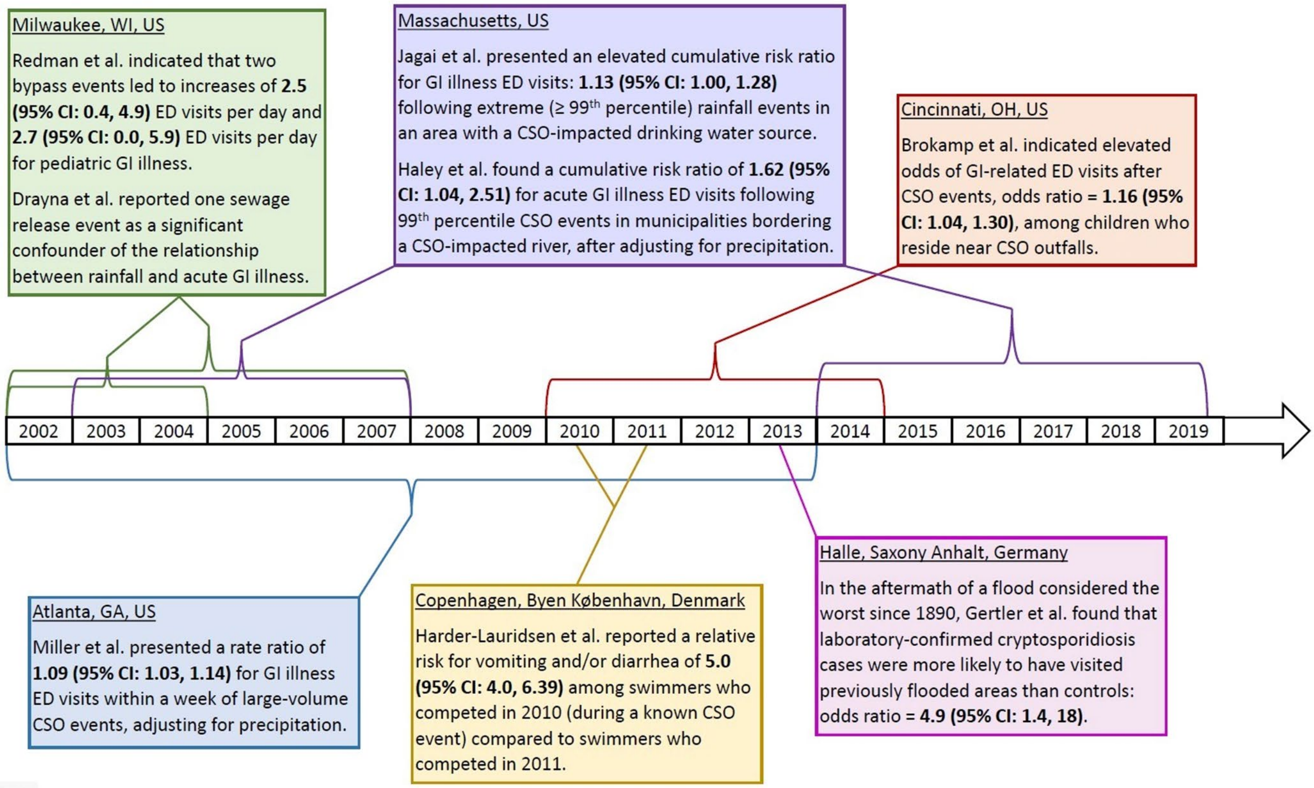

Fig. 3 Timeline of CSO Exposure Periods and Reported Associations with GI Illness. (CSO: combined sewer overflow, GI: gastrointestinal, ED: emergency department, CI: confidence interval)

to obtain information related to symptoms of GI illness [40, 41], allowing subclinical manifestations of GI distress to be counted as cases. According to results of a cross-sectional telephone survey of 2,433 adult residents of New York City, every ED visit for diarrheal illness in 2003 represented approximately 251 diarrheal illnesses among adult city residents [46]. A more recent study based on 2016–2017 survey data from Oregon and Washington, US, found that nearly one fifth of people with acute gastroenteritis symptoms sought medical care, when medical care included telehealth, email exchange via patient portal, and urgent care center visits, in addition to ED visits [47]. Other analyses of the relationship between extreme rainfall and GI illness have used nurse advice calls as a measure of GI cases [48, 49], and seasonal patterns of advice calls, in comparison to primary care visits, suggest that calls provide a better measure of viral infection incidence than visits [49]. While studies that relied on ED visit data included diagnosis codes for acute GI illness, they also included diagnoses of unspecified gastroenteritis and colitis, which are sometimes symptoms of chronic diseases [38, 39, 42–45]. All eight of our included studies treated GI illness as a dichotomous outcome, rather than as an ordinal or semi-continuous measure that could better account for different levels of severity [50]. However, Harder-Lauridsen et al. [40] tested two different GI illness case definitions and analyzed the duration of GI symptoms, an important factor in determining case severity [50].

Exposures

All included studies examined acute exposures, with lag periods between exposure and outcome ranging from zero days (same day as the CSO event) to three weeks (Table S3). Exposure metrics examined varied across studies, with two examining precipitation and incorporating potential CSO impact [39, 42]; two examining presence or absence of activities in sewage contaminated or potentially contaminated areas [40, 41], and four examining presence or absence of CSO or bypass events, including information on discharge volume or residential proximity [38, 43–45]. There is limited information on individual-level exposures and water interactions. Only one study assessed the impact of sewer infrastructure improvements, and the authors found that improvements to infrastructure significantly reduced the number of CSO events in Atlanta, GA, but did not meaningfully change the association between CSO events and GI illness [44]. While high-volume CSO events have been significantly associated with increased ED visits for GI illness [44, 45], there was not sufficient evidence to support a linear dose-response relationship between CSO discharge volume

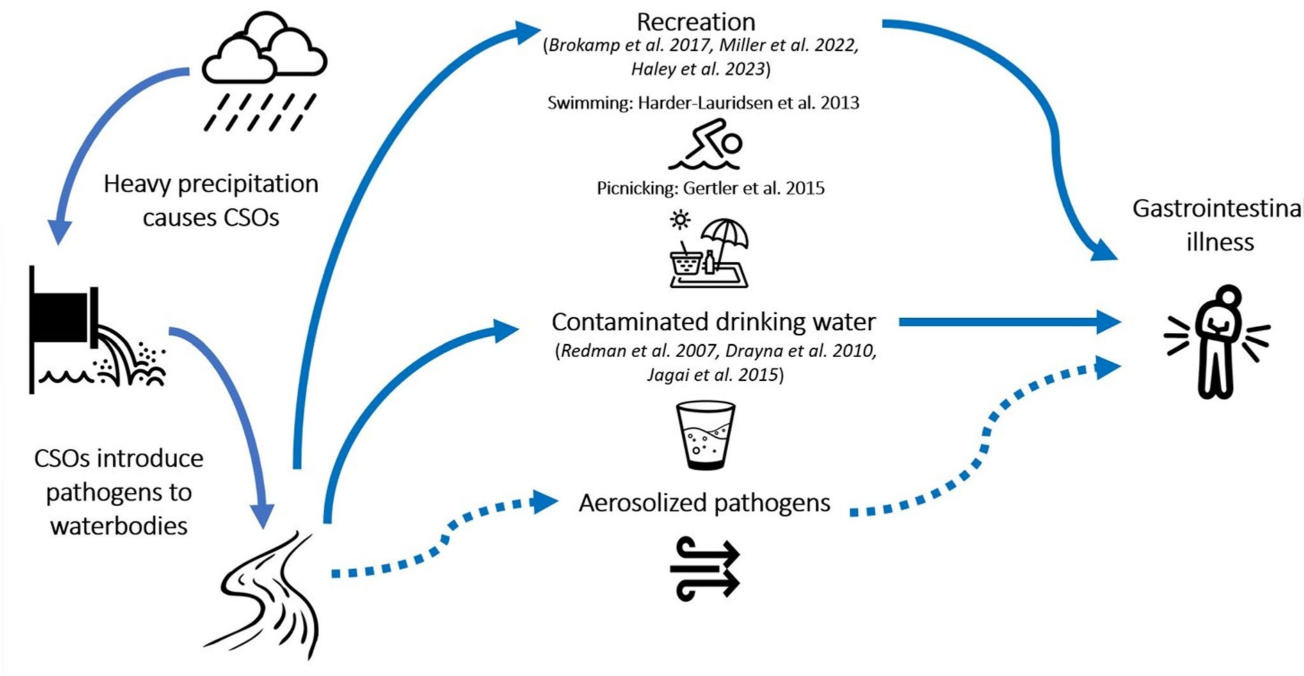

Fig. 4 Different Routes of Exposure to Combined Sewer Overflows (CSOs). Time series and self-matched studies are in italics. (Source of images: "The Noun Project" https://thenounproject.com/)

and GI illness in Atlanta [44]. Additionally, in Milwaukee (Wisconsin, US), a sewage release event that was less than half the discharge volume of the largest event had approximately the same impact on daily rate of ED visits for diarrheal illness [38].

Subpopulations and Potential Modification

Half of the studies in this review focused on pediatric study populations. Gertler et al. [41] investigated an outbreak of *Cryptosporidium* among German kindergarteners (3–6 years old), while Redman et al. [38], Drayna et al. [39], and Brokamp et al. [43], studied emergency department visits for gastrointestinal illness among patients 0–18 years old (Table 2). Two studies in this review investigated acute GI illness outbreaks among specific populations—triathletes who swam in a CSO-impacted waterway in Denmark [40] and kindergarten children in Halle, Germany [41]. Questionnaires of participants in both studies provided information on individual behaviors that may have resulted in exposure, namely unintentional ingestion of water while swimming and visits to a floodplain after a large flooding event that included CSOs. Unique among the studies included in this review, Jagai et al. [42] performed an age-stratified analysis of the association between extreme rainfall and ED visits for each of three study regions: CSO exposure by drinking water, CSO exposure by recreation, and no CSO exposure. Positive associations were found among all age groups in the region of Massachusetts where drinking water systems rely on a CSO-impacted river within 8 days of a 99th percentile precipitation event, with especially strong associations observed among individuals 65 or older and children 5–19 years old [42].

Discussion

This review summarizes the epidemiological research to date that has examined a potential association between CSOs and GI illness in humans. Among the eight included studies, some study populations included all ages [42, 44, 45], others were specific to pediatric populations [38, 39, 41, 43], and one specifically focused on physically-fit adults [40]. Some of the included studies hypothesized that human exposure to CSOs is likely to occur through drinking water [38, 39, 42], while the findings of other studies suggested recreational exposure routes [43–45], and two studies specifically examined swimming and picnicking recreational exposures through questionnaires [40, 41] (Fig. 4). All eight studies contributed scientific evidence supporting a positive association between CSOs and GI illness (Fig. 3).

Although multiple studies presented discharge volume data for CSOs [38, 39, 44, 45], there was not evidence of support for a linear exposure-response relationship between volume of event and risk of GI illness. It is possible that in very large CSO events, the concentration of pathogens is diluted by the large contribution of stormwater [44]. Previous work on the "Concentration-Dilution Hypothesis" has suggested that a period of dry weather preceding a heavy rainfall event can increase the effect of rainfall on diarrheal disease incidence [51]. For example, water-borne disease outbreaks in England and Wales were found to be associated with excess rainfall in the previous week and low rainfall in the three weeks preceding the week of the outbreak [3]. A similar pattern was observed in Canada, where the effect of extreme precipitation on cryptosporidiosis and giardiasis was greater following a dry period [52]. The phenomenon of pollutants accumulating on land during dry periods, and then appearing in high concentrations at the beginning of the first extreme rainfall event has been referred to as the "first flush" phenomenon [53], and higher pollutant concentrations in stormwater runoff after longer antecedent dry periods have previously been observed in urban areas [54]. Future studies of the relationship between CSOs and GI illness would be more thorough if antecedent dry periods of multiple lengths were tested as predictors of GI illness, in addition to testing different lag periods between CSO events and disease incidence.

Several studies included in this review investigated or hypothesized potential exposure pathways, with implications for interventions to protect public health, but few studies include individual-level exposure data. Two pathways in particular—recreational exposure and ingestion of contaminated drinking water—are the primary exposure routes hypothesized in the literature on CSO health impacts (Fig. 4). Recreational exposure consists of incidental ingestion of CSO-associated pathogens during direct (e.g., swimming) or limited contact (e.g., fishing, boating, picnicking) recreational activities. Drinking water contamination may result from CSO discharge to a surface waterbody that serves as a drinking water source and inadequate treatment prior to distribution to households. Two studies that investigated outbreaks provide some of the most direct evidence of acute GI illness occurring after recreational exposure to CSO discharge [40, 41], while a third, Brokamp et al. [43], provided additional support for this pathway by examining population subsets based on residential location. Studies of acute GI illness following CSO events that investigate potential exposure through drinking water contamination have, to date, utilized effect measure modification exclusively to assess the importance of drinking water source [38, 42, 45]. Besides recreational exposure and ingestion of contaminated drinking water, there may be additional exposure routes linking CSOs to health outcomes. For example, the presence of enteric pathogens in urban and coastal aerosols suggest that human exposure to sewage-contaminated surface water can also occur through aerosol inhalation [55, 56]. Exposure to aerosolized waterborne pathogens from CSOs could result in respiratory illness or outcomes primarily associated with airborne pathogens, such as COVID-19 [57]. While some initial work has been done to assess the association between CSOs and respiratory illness [43], these outcomes fall outside of the scope of this review. More research is needed to assess the role of aerosol inhalation in human exposure to CSO-associated pathogens and possible health outcomes (Fig. 4). Further, there are persistent gaps in our understanding of the relative importance of different exposure pathways due to a lack of individual-level exposure data in most studies, especially those that hypothesize exposure through contaminated drinking water. In the absence of detailed information on CSO exposure routes, quantitative microbial risk assessments (QMRAs) have been used to estimate human health impacts. For example, a QMRA for CSO-impacted sites in Philadelphia, PA, based on pathogen concentration data and observational data of recreational exposures, found that recreating within one day after a CSO event increased the risk of acute GI illness by 39–75%, relative to recreating more than one day after a CSO event [58]. Another QMRA based near a discharging CSS in Newark, NJ estimated that the probability of a recreator – someone in direct contact with surface water through activities such as swimming or water-skiing – contracting GI illness from incidental ingestion of either fecal *Streptococcus* or *Enterococcus* bacteria in the water was approximately 0.70 for each pathogen [59]. One QMRA examined the probability of illness for an exposure scenario that is very similar to the aftermath of the flooding event described in Gertler et al. [41]. In this scenario, a baby plays on the grass in a park where flood water had previously deposited sewage-related pathogens; it is estimated that the baby has a 0.03-17% probability of illness due to hand-to-mouth pathogen transfer [60]. The performance of drinking water treatment plants was found to be an important modifier of the risk of microbial contamination of drinking water due to upstream CSO events along the Ottawa River in Canada, estimated through QMRA methods [61].

Susceptibility to GI pathogens and severity of acute GI illness are not uniform across all populations, with young children, people over the age of 65, and immunocompromised individuals most susceptible to acute GI illness and most likely to experience severe symptoms [62]. Children can also be more vulnerable to pathogens during water-based recreation because they tend to engage in activities such as swimming for longer periods of time and swallow more water during those activities than adults [63, 64]. Many of the included studies focused on pediatric populations [38, 39, 41, 43], while one study examined age-stratified associations [42]. Additional studies that include residents of all ages but investigate effect measure modification by age and immune status would provide insight into the potentially unequal impact of CSO events among susceptible populations.

Further Research

The geographic scope of this review was not limited a priori to any particular region of the world. However, all studies that met inclusion criteria were conducted in the United States or western European countries. CSSs are located in urban centers in countries throughout the world including Japan [65], China, South Korea [17], New Zealand [66], Mozambique [67], Côte d'Ivoire [68], Argentina [69], and Brazil [70]. Data on CSSs are not readily available in all countries, posing a challenge to a comprehensive summary of the global distribution of CSOs [17]. Policies impacting CSO control and mitigation vary between countries [17], and variation in exposure risk due to recreational and direct contact usage of waterways, drinking water treatment processes, and projected changes in precipitation patterns differ across countries as well. Additional research is critically needed to understand the scope of the association between CSO discharge and human health globally.

The focus of this review is adverse health outcomes associated with CSO events, but there are other types of sewage discharge events with implications for GI illness that warrant additional research. For example, one of the mitigation strategies for CSO events is a process by which wastewater treatment facilities partially treat influent prior to discharge into the receiving waterbody during times of increased flow [71]. The process involves routing screened and clarified wastewater around the biologically active portion of treatment—referred to as secondary treatment—and disinfecting prior to blending with fully treated effluent or discharging directly into the receiving waterbody [72]. Several names apply to this general type of process including secondary sewage bypass, high-flow or wet weather treatment, or blended discharge. Wet weather treatment that involves only partial treatment of wastewater can occur in both CSSs and sanitary sewer systems, which transport wastewater and stormwater separately [73]. Public health concerns related to wet weather treatment are similar to those for CSO events, given that microbial contaminants—especially viral and protozoan enteric pathogens—have been documented at higher concentrations in partially treated effluent compared to fully treated effluent [74]. Redman et al. [38], included in this review, does use sewage bypass events to characterize exposure, but this is the only study we are aware of that looks at health outcomes in relation to partially treated effluent. Sewage overflows can also occur in sanitary sewer systems; contrary to CSOs, sanitary sewer overflows (SSOs) can occur anywhere in the sewer system, including inside buildings, along streets, and into waterways. Sanitary sewer systems are not designed to overflow during wet weather, but extreme precipitation can still exacerbate these events. Although outside of the scope of this review, several studies suggest that SSOs can contribute to increased risk of GI illness [75, 76]. Further research on the impacts of extreme precipitation events in the context of urban water infrastructure would benefit from including CSOs, wet weather treatment, and SSOs as potential exposure events to fully capture the risk of GI illness associated with wastewater treatment challenges in urban settings.

Conclusion

The positive association between CSO events and GI illness observed in multiple studies (Fig. 3) is concerning due to projections of increased extreme precipitation events in certain regions of the world. For example, CSO events have been predicted to increase in frequency by 50–120% by the end of the 21st century in the Great Lakes region of the US [8]. In Vancouver (British Columbia, Canada), precipitation is expected to increase during the months of October through March, which could lead to higher annual rates of cryptosporidiosis and giardiasis if drinking water treatment and wastewater infrastructure are not improved [31]. Adjustments to wastewater infrastructure in the United Kingdom (UK) have been considered, and it is likely that stronger treatment of wastewater will be necessary in future summers [77]. In New Zealand and the UK, the impact of increasing climate variability on CSO occurrence and discharge volume is not limited to rainfall effects, but also includes the effects of sea level rise [66, 77]. In this scoping review, we provide a summary of eight studies that estimated the impact of CSO events on human GI health. Our review includes one study that analyzed the effect of infrastructure improvements on CSO frequency and found a significant reduction in the number of CSOs [44]. As changing precipitation patterns place further stress on CSSs in certain regions of the world, additional infrastructure improvements might limit the public health burden of GI illness. The principles highlighted in this review may be used to inform Health Impact Assessments of interventions that affect sewage system infrastructure. In addition, our review might inform policy and guidance on recreational use of water bodies impacted by potential CSOs or waste discharges. The information in this review could also be used to improve mathematical models of risk, such as in the QMRA framework, to better predict timing and extent of risks associated with CSOs.

Key References

- B. M. Haley et al., "Association between combined sewer overflow events and gastrointestinal illness in Massachusetts municipalities with and without river-sourced drinking water, 2014–2019," *Environmental Health Perspectives*, vol. 132, no. 5, 2024.

  Findings from this study indicate a non-linear relationship between CSO discharge volume and gastrointestinal illness, and that CSO-GI associations were independent of precipitation.

- A. G. Miller, S. Ebelt, and K. Levy, "Combined Sewer Overflows and Gastrointestinal Illness in Atlanta, 2002–2013: Evaluating the Impact of Infrastructure Improvements," *Environmental Health Perspectives*, vol. 130, no. 5, May 2022, Art. no. 057009.

  Findings from this study show that infrastructure improvements reduced the number of CSOs, while the CSO-GI association remained.

  US Environmental Protection Agency (EPA). (2023, 6-19-2024). *Combined Sewer Overflows (CSOs)*. Available: https://www.epa.gov/npdes/combined-sewer-overflows-csos.This page provides important background information about CSOs, along with CSO outflow locations across the United States.

- W. B. Perry, R. Ahmadian, M. Munday, O. Jones, S. J. Ormerod, and I. Durance, "Addressing the challenges of combined sewer overflows," *Environmental Pollution*, vol. 343, p. 123225, 2024/02/15/ 2024.

  This paper provides a review of CSO properties and their effects on ecosystems, people, and economies, highlighting the broad spectrum of potential impacts.

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Data Availability No original datasets were generated or analysed during the current study.

Declarations

Ethics Approval and Consent to Participate This article does not contain any studies with human or animal subjects performed by any of the authors.

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