ENVIRONMENTAL RESEARCH
HEALTH

PURPOSE-LED PUBLISHING™
Part of the ENVIRONMENTAL RESEARCH SERIES

PERSPECTIVE • **OPEN ACCESS**

Sanitary sewer overflows, household sewage backups, and antibiotic-resistant bacteria: the new frontier of environmental health risks and disasters

To cite this article: Marccus D Hendricks and Rachel E Rosenberg Goldstein 2025 *Environ. Res.: Health* **3** 013001

IOP Publishing Environ. Res.: Health 3 (2025) 013001 https://doi.org/10.1088/2752-5309/ad8d05

ENVIRONMENTAL RESEARCH
HEALTH

CrossMark

OPEN ACCESS

RECEIVED
16 August 2024

REVISED
20 October 2024

ACCEPTED FOR PUBLICATION
30 October 2024

PUBLISHED
19 November 2024

PERSPECTIVE

Sanitary sewer overflows, household sewage backups, and antibiotic-resistant bacteria: the new frontier of environmental health risks and disasters

Marccus D Hendricks[1,*] and **Rachel E Rosenberg Goldstein**[2]

[1] Urban Studies and Planning Program, University of Maryland, College Park, Maryland, United States of America
[2] Department of Global, Environmental, and Occupational Health, University of Maryland, College Park, Maryland, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: mdh1@umd.edu

Keywords: wastewater, infrastructure, public health, bacteria, built environment, methodologies

Supplementary material for this article is available online

Abstract

Untreated sewage discharges leading to environmental contamination are increasingly common in communities across the globe. The cause of these discharges ranges from sewer lines in disrepair, blockages, and in the era of more extreme wet weather events, the infiltration of stormwater into the system during heavy downpours. Regardless of the driver of these events, the aftermath results in raw sewage spilling into local waterways, city streets, and commercial and residential structures. Historical research in public health has thoroughly documented the connection between exposure to untreated sewage and waterborne disease. Recent research has detected antibiotic-resistant bacteria at wastewater treatment facilities at a time when deaths by antibiotic-resistant infections are on the rise. However, no research has explored the exposure pathways of antibiotic-resistant bacteria during sanitary sewer overflows and household-level sewage backups. In this commentary, we aim to introduce this new frontier of environmental health risks and disasters. To do this, we describe the history of modern sanitation and sewer infrastructure with a particular focus on wastewater infrastructure in the U.S. We also explore emerging risks and current methods for identifying antibiotic-resistant bacteria in the environment. We end with future directions for interdisciplinary scholarship at the nexus of urban planning, engineering, and public health by introducing the Water Emergency Team (WET) Project. WET is a community-based multi-method effort to identify environmental risks in the aftermath of household backups through (1) residential surveys, (2) indoor visual inspections, (3) environmental sampling, and (4) laboratory processing and reporting. Our hope is that by introducing this comprehensive approach to environmental risks analysis, other scholars will join us in this effort and ultimately towards addressing this grand challenge of our time.

1. Introduction

The U.S. Environmental Protection Agency (EPA) estimates that there are 23 000–75 000 Sanitary Sewer Overflows (SSOs), the release of untreated sewage from a municipal sewer system, per year in the U.S, which is most likely a severe underestimate of the true extent of these events [1]. Likewise, this does not include illicit discharge or backups into homes or buildings. Due to the interconnected nature of these systems by design, one can assume that when SSOs occur, it is likely that basement backups do as well, but the exact number and extent of these backups are unknown. SSOs occur across the U.S. and around the world, often in older cities with aging infrastructure. For example, in Baltimore City, MD (USA) alone, these events have persisted for decades with tens of thousands of reported events and hundreds of millions of gallons of sewage spilling into the streams, rivers and eventually the Chesapeake Bay, as well as city streets and homes. In fact, in January of 2024, more than 14 million gallons of sewage were discharged in Baltimore in just one day [2].

The comprehensive investigation of these events is critical because urban planning and public health studies have consistently identified associations between poor sanitation and disease. Modern stormwater and sewer systems are critical lifesaving infrastructures, however, failure to maintain and rehabilitate these systems, as well as climate change stresses, have created pre-modern circumstances (e.g. unsanitary environments that included several sanitation-related public health risks, prior to the invention and installation of contemporary sewer infrastructure) in cities across the world. These risks are particularly evident in marginalized urban neighborhoods with poorer stormwater and sanitation infrastructure and public works services [3]. The Baltimore sewer system has frequent SSOs due to an old and failing system and more frequent intense rainfall events associated with climate change. As a result, communities are persistently exposed to raw sewage, likely containing waterborne pathogens and possibly antibiotic-resistant (AR) bacteria. In fact, a Washington Post article, noted that aging sewer infrastructure was to blame for a 2022 E.coli contamination of the city's drinking water [4].

In this commentary, we open by providing some background context on modern sanitation infrastructure and the nature of sanitary sewer overflows and basement backups. We then unpack the emerging pathogenic risks associated with these events, including antibiotic resistant bacteria. Next, we outline current methods for identifying and recovering antibiotic resistant bacteria in the environment. Lastly, we offer future directions for this type of research and introduce one such multimethod approach, the Water Emergency Team (WET) project.

2. Background

2.1. Invention of modern sanitation infrastructure

There are well-documented reports that humans have been working at the intersection of public health and urban planning since the inception of some of the world's earliest civilizations, including ancient Egypt and the Indus Valley. Modern practices as we know them today, date to the nineteenth century England when unsanitary urban environments led to high rates of death and disease [5–7]. City dwellers often experienced low quality of life and low life expectancy as a result of environmental exposures related to unsanitary housing and occupational health hazards, as well as drinking water contaminated with untreated sewage [8, 9]. A breakthrough that decreased drinking water contamination came when a connection was made between disease transmission pathways and environmental exposures. In London, the epidemiologist John Snow mapped a cholera outbreak based on individuals reporting symptoms, tracing its origins back to the handle of a local water pump [10]. In Snow's time, cholera was rampant and deadly. As the story goes, Snow removed the water pump handle, effectively eliminating the source of the disease transmission and stopping the outbreak.

The story of John Snow removing the handle of the Broad Street Pump and ending the cholera epidemic [11–13], demonstrated Snow's theory of water-borne transmission led to immense improvements in community public health [14]. By connecting where and when people were falling ill, researchers were able to determine the community water source was the source of the contamination. This history marks what some people consider to be the beginning of public health practice, it also marks a time when a direct connection was drawn between infrastructure, community contamination, and health, which led to improved community health and wellbeing. In 1999, Dr Martin Melosi published The Sanitary City: Urban Infrastructure in America from Colonial Times to the Present, this work chronicles the history and importance of the nation's sanitary systems including the drinking water supply, wastewater and solid waste disposal systems.

The installation of sanitary sewer networks and drinking water treatment systems in industrial cities, is considered one of the top ten public health achievements of the twentieth century by the Centers for Disease Control and Prevention (CDC) because of its role in the significant reduction in infectious disease [15]. By reducing exposures and the risk of exposure through sanitary infrastructure and clean water systems, communities have increased lifespans and better quality of life [16]. However, centuries later, communities in the US and around the world are experiencing a reemergence of sanitary issues that were thought to have been addressed through earlier infrastructure investments.

Infrastructure systems of all kinds, including sewerage, must be regularly invested in and maintained over the life cycle of these systems. Likewise, these systems must be routinely evaluated for updates and modifications to meet current conditions, including capacity and bacteria surveillance for proper treatment. Sewage still contains pathogens and likely new pathogens that can be harmful to human health. Disease transmission routes are important for conceptualizing the multiple hazards and threats posed by sewer overflows and basement backups. Direct transmission of diseases can occur from exposure to contaminants

Table 1. Overview of overflow and backup terminology.

Concept	Definition
Sanitary sewer overflow	When a ***separated*** sanitary sewer system releases untreated sewage or sewage-laden stormwater into the environment before it reaches the wastewater treatment facility due to disruption in flow or infiltration of stormwater
Combined sewer overflow	When a ***combined*** sanitary sewer system releases untreated sewage or sewage-laden stormwater into the environment before it reaches the wastewater treatment facility due to capacity issues of managing both sewage and stormwater in the same line
Basement backup	When a separate or combined sanitary sewer system releases untreated sewage or sewage-laden stormwater into a building, structure, or home, usually in the ***basement*** area, and infiltrating through a line on the property or a bathroom plumbing fixture

within the household or the public domain. Disease transmission can also occur when people are exposed to water or food that has been contaminated [17]. For the purposes of sewer overflows and basement backups, disease transmission through the contamination of waterways and recreational water bodies, streets, homes, and drinking water sources are the primary transmission routes of concern. Pathogens contained in sewage can cause a variety of negative health outcomes including gastroenteritis [18–20].

2.2. Wastewater infrastructure in the United States

Cities in the US began planning for and constructing wastewater infrastructure systems in the late 1880s [21]. As of 2024, around 75% of Americans are served by a centralized wastewater treatment plant versus a septic tank [22]. Most US cities have either a combined or separated sewer system. Combined sewer systems are designed to carry both sanitary wastewater and stormwater and route the two either for direct deposit into local waterways (e.g. stormwater) or to be treated and then deposited (e.g. wastewater). In the US, combined sewer systems are primarily located in Northeastern cities and the Great Lakes region. Roughly 860 municipalities in the US have combined sewer systems, and those systems serve about 40 million people [23]. Separate sewer systems on the other hand have two separate systems for transporting stormwater and wastewater along their respective pathways. Both types of systems can experience issues over time affecting their level of service. While separated sewer systems alleviate some of the capacity issues experienced by combined sewer systems [24], aging separated systems can face similar challenges due to inadequate maintenance and repairs.

In the US, urban communities are facing significant challenges with both their combined and separate stormwater and wastewater infrastructure causing sewer overflows and basement backups into homes and buildings. In 2021, the American Society of Civil Engineers (ASCE) gave the US wastewater infrastructure a cumulative grade of 'C-' on a grading scale from A+ to D− [25]. The primary cause of these challenges is the original wastewater infrastructure is aging, and local governments have not been able to keep up with needed maintenance and repairs [26]. Aging sewer infrastructure poses an imminent threat to human and ecological health because when overflows occur in the system raw sewage is released into the environment, either in streams, roads, or in some cases in residential homes and commercial buildings. Sewer overflows are more frequently associated with combined sewer systems because any intense precipitation event could lead to an overflow. Both combined and separated sewer systems can result in sewer overflows from wet weather events. Combined sewer overflows (CSO) occur when a large rain event causes a capacity issue in the sewer system, leading to an overflow [24]. Similarly, sanitary sewer overflows (SSOs) occur when stormwater infiltrates the pipes through cracks or other openings in the system and the capacity of the pipes is surpassed [27]. In table 1, we organize and further define what it means for these two types of systems (e.g. combined and seperated) to overflow and the concept of a basement backup.

2.3. Sanitary sewer overflows and household sewer backups

Sewer overflows are harmful to human and ecosystem health because they expose communities to untreated sewage through outfall releases into local waterways, sewage overflows in public spaces [28], and basement backups in individual homes and buildings [29, 30]. As seen in figure 1, sewer basement backups can be caused by blockages in the lateral pipes on a homeowners property or by pressure in the main pipes on city property. The location of the blockage is important in determining whether the responsibility falls with the homeowner or the municipal government. Sewer overflows and basement backups can occur during dry events and wet weather events. Dry events that cause sewer overflows occur when there is a blockage in the pipes, could include a buildup of oil, infiltration of tree roots, or other blockages that build over time. Wet

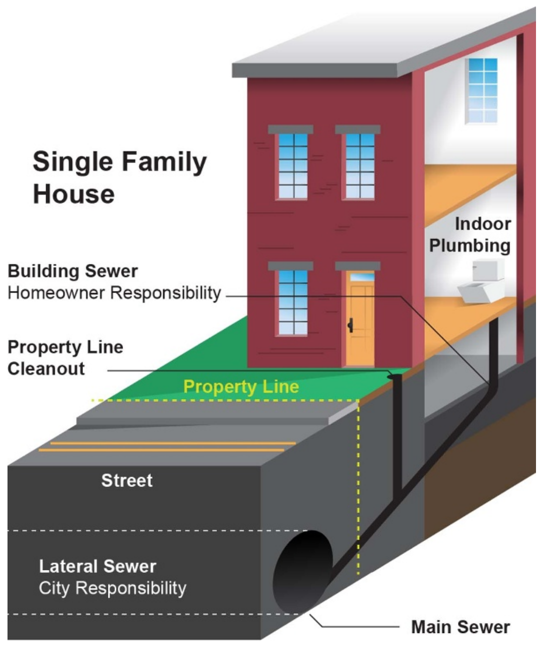

Figure 1. Lateral/Building Sewer Diagram.

weather events occur when rainfall overloads the sewer systems creating a capacity issue [31]. Global climatic change and more frequent and intense wet weather events will add even more pressure on these aging systems.

3. Emerging risks

In addition to the risk of gastroenteritis from household exposure to sewage, other illnesses can result from sewage exposure including AR bacterial infections such as those caused by methicillin-resistant *Staphylococcus aureus* (MRSA) and vancomycin-resistant enterococci (VRE). MRSA and VRE have been detected in wastewater and home environments [32–36]. Proximity to a wastewater treatment plant discharge has been associated with higher occurrences of *S. aureus* in freshwater samples [37]. Similarly, *E. coli* levels increased in Lake Michigan after heavy precipitation with the causative source identified as combined sewer overflows and SSOs [38]. MRSA has also been detected from home-environment surface samples, but never in homes where SSOs and backups typically occur [39]. If *S. aureus*, and MRSA as well as VRE, are present in homes experiencing SSOs and backups, they could represent an important transmission route for AR bacteria.

Alarming increases in AR bacterial infections in general, and particularly in community-associated infections among individuals that have not been exposed to healthcare settings, have stoked a major public health crisis. Around 3 million AR infections occur in the U.S. each year, contributing to almost 50 000 deaths, and these infections are expected to increase over time [40]. Among AR pathogens, MRSA and VRE are considered serious threats. Black and African American communities shoulder disproportionately higher rates of AR bacterial infections. From 2005–2014 there were higher community-associated MRSA infections rates among Blacks (aRR, 2.78; 95% CI, 2.30–3.37) compared to whites [41]. Research over the past few decades has confirmed the presence of AR bacteria in the environment, yet it remains unclear to what extent these environmental sources, including the wastewater and home sewage backups, contribute to the high infection rates at specific locations. These studies have used a variety of methods for detecting and monitoring including culture-based methods, PCR, sequencing, and a combination of these methods. If MRSA and VRE are present in SSOs and backups, it expands the population that is possibly exposed to these serious AR bacteria and presents an opportunity to control the spread of these infections.

4. Current methods for identifying AR bacteria in the environment

Great strides have been made in understanding the various potential sources of ARB and antibiotic-resistant genes (ARGs), from focusing solely on healthcare-associated environments to more broadly encompassing multiple natural and built environments [42, 43]. An important potential source of AR bacteria in the built environment are wastewater treatment plants and their receiving water bodies [42–44]. Studies have identified MRSA, VRE, MDR/ESBL *E. coli*, carbapenem-resistant Enterobacteriaceae (CRE), MDR-*Pseudomonas*, and Quinolone-resistant *Aeromonas*, among others, and ARGs, throughout the wastewater treatment train, including in treated wastewater (effluent) [34, 35, 42]. Further, MRSA, vancomycin-resistant *S. aureus*, and, antibiotic-resistant *E. coli, Klebsiella pneumoniae*, and ARGs, have been found in surface waters that receive treated wastewater (effluent) [43–45].

Although identifying ARB and ARGs in these environments is critical for identifying possible additional sources; to fully understand the public health risks of ARB in these environments it is also critical to evaluate the magnitude and frequency of human exposure to wastewater, now that we know ARB are present in this water source. From the wastewater treatment plant, the population most directly exposed to wastewater are the wastewater treatment plant workers themselves. A few studies have evaluated exposure to ARB among wastewater treatment plant workers, most notably the AWARE study in Europe, but the number of workers at these plants is generally small [46–48]. WWTP workers are also more directly, and more frequently, exposed to raw sewage than residents impacted by SSOs or backups, but this work still provides important insights into exposure risks from contact with sewage. Interestingly, the AWARE study found that AR exposure risks differed by country and when comparing those working at wastewater treatment plants (WWTPs), those living near WWTPs, and those living further from WWTPs [46, 47]. Residents living closer to WWTPs were more likely to have ESBL-EC in their stool samples compared to both WWTP workers and those living farther from WWTPs [46]. There was no increased risk of ARG presence in fecal samples among wastewater treatment workers compared to a group of control participants [47]. Others have sampled receiving water bodies and even collected biological samples from those exposed recreationally to these surface waters, finding both ARB and ARGs [43].

Since the COVID-19 pandemic, there has also been a rapid expansion of wastewater surveillance for disease tracing, including a growing movement to track ARB. Wastewater surveillance is an excellent tool for identifying trends in a population, 6–14 d ahead of infections or hospitalizations being reported [49]. These data coupled with research from wastewater treatments plants cements wastewater as a recipient and source of ARB in the environment. Knowing that when SSOs and basement backups occur this means that raw wastewater enters homes without making it to the WWTP and receiving treatment means that we have an urgent need to understand ARB exposure at the household and community level.

5. Future directions: household and community level methods

5.1. Need for rapid-response to study problem

SSOs and backups often occur during extreme precipitation events and thus require rapid response. Typical academic exposure assessments involve advanced planning and complicated logistics, often missing critical exposure periods. For example, during our pilot study we coordinated sampling events with our community partners and participants based on their availability instead of when SSOs or backups were occurring. By sampling based on availability, the majority of participants had cleaned up the sewage in their homes long before we arrived, and our samples often measured bacteria that had survived long periods since sewage exposure and/or cleaning. There is a need to capture exposures as they occur, improving our ability to provide communities with results in a timely fashion, so that they can quickly engage in proper clean-up and mitigation as well as access emergency funds.

5.2. Community-engaged partnerships to address this crisis

In addition, sewage exposure and indoor housing quality have not been heavily studied from an environmental justice perspective compared to more traditional approaches. Environmental monitoring and exposure assessment research can be extractive when conducted in communities if the research is investigator-driven instead of driven by the community. Research in this area should prioritize work with community leaders as full research partners for study design, execution, and ultimately community benefit.

6. Water emergency team (WET) project

We have established the community-driven Water Emergency Team (WET) to respond to SSOs and backups in Baltimore, MD homes, and underserved African American communities in the broader District of Columbia/Maryland/Virginia metro region.

Baltimore (figure 2) is the largest city in the State of Maryland and located in the Mid-Atlantic region of the US eastern seaboard. Baltimore City has a population of593,490, with 63% Black or African American residents. The 2018 median household income in Baltimore was $48 840 with 18.9% of the city living in poverty. WET completes a series of activities as part of a comprehensive assessment of experiences and

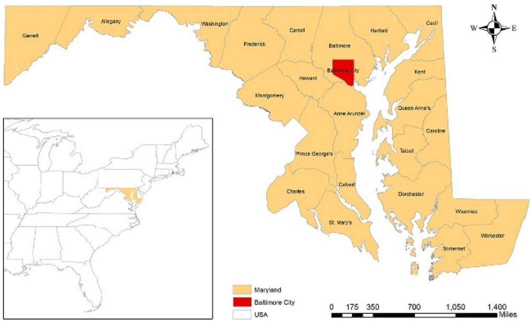

Figure 2. Map of Baltimore, MD, USA.

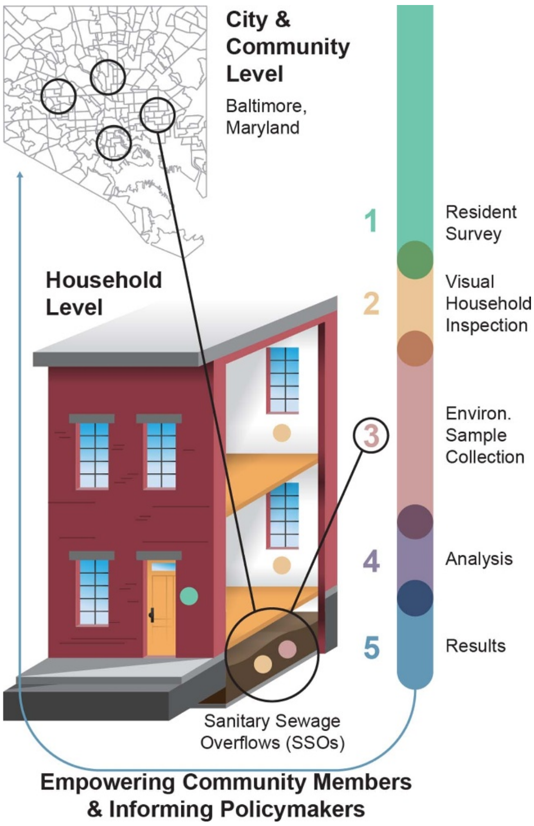

Figure 3. Water Emergency Team (WET) Project Components and Approach.

impacts from SSOs and backups at the household-level. Figure 3 outlines this process visually with steps including, (1) residential survey; (2) visual household inspection; (3) environmental sample collection of standing water and surface swabs from impacted indoor areas; (4) analyses of samples for fecal indicator and AR bacteria; and (5) results dissemination with efforts to empower community members and inform policymakers. WET collects samples in neighborhoods identified by our community partners as experiencing frequent SSOs and backups and those identified through publically available reports of SSOs. We recruit participants from homes impacted by sewage as well as control homes in the same or nearby neighborhoods that have not been impacted by sewage. WET's goal is to rapidly and accurately detect AR bacteria and fecal indicators in collected samples. WET returns sampling results to the community, empowering them to mitigate contaminated areas and access emergency resources. WET harnesses the power of student volunteers who are actively engaged throughout the various aspects of the project including field sampling, community outreach, and communication.

6.1. Overall approach

1. ***WET Rapid Response Team.*** WET recruits participants by canvassing previously affected neighborhoods across the region, passing out flyers and business cards so that community members can reach WET as SSOs and backups occur. We also use available spatial data on flooding and reported SSOs to select vulnerable areas and recruit participants at community events.
2. ***Visual Household Inspection.*** WET conducts visual household inspections to identify proximate and contextual factors that shape environmental exposures connected to water damage such as water stains, mold and mildew using inspection forms and validated check lists. These inspections allow us to more comprehensively connect individual and place-based drivers of indoor environmental quality with the overall health of residents affected by SSOs and backups.
3. ***Surveys.*** WET conducts surveys among Baltimore residents using Qualtrics to capture information on household and individual experiences with vulnerable infrastructure and flooding, including SSOs, risk communication, and public works response and management. The survey also gauges experiences and perceptions related to social capital and city notification, response, and infrastructure rehabilitations. The survey is a mixture of closed and open-ended questions but primarily quantitative in nature. For example, one question asks, 'When did you last notice the sewage or water in your home?' with open-ended responses including 'hours:__, days: __, weeks:, months:__'. We also ask, 'What cleaning/remediation did you do after the last sewage or water event (select all that apply) ?' with response options including 'none, soap and water, sanitizer, wet vacuum, and other (please specify)'.
4. ***Sample Collection and Analysis.*** WET collects water and surface swab samples directly from basements or other impacted areas of participating homes using sterilized sampling materials. Fecal indicator bacteria, including *E. coli* and enterococci, and AR bacteria, including MRSA and VRE, are isolated from samples using membrane filtration followed by growth in enrichment broths or selective agars. These methods have been successfully used by the team in previous wastewater focused studies [34, 35]. All presumptive isolates are confirmed by biochemical testing followed by polymerase chain reaction (PCR).
5. ***Translating Results for Community Empowerment.*** WET provides sampling results to participants through a 'report card' that provides bacterial results as well as background information on the target bacteria, mitigation and cleaning procedures, and additional resources. All bacterial results are reported as present or absent, except for E. coli and enterococci in water samples as the U.S. EPA sets concentration-based recreational water standards for these fecal indicator bacteria. Each result is color coded in light red for 'present' bacteria and light green for 'absent' bacteria. Sample report cards for surface and water samples can be found in the appendix.

6.2. Preliminary findings

Since August 2023, WET has collected over 101 samples, surveys, and household visual inspections from homes impacted by SSOs or backups, attended 23 community events, and interacted with over 1,000 community members. Preliminarily, ARB have been detected in 31% (31/101) samples and fecal indicator bacteria have been detected in 74% (75/101) samples.

7. Conclusions

SSOs and backups are chronic, under-studied infrastructure and public health threats that likely disproportionately impact low-income communities of color. Climate change will only continue to stress the U.S.'s crumbling infrastructure, disproportionately impacting marginalized communities exposed to raw sewage. There is an urgent need to better understand risks from SSOs and backups at the household and community level, building on decades of research showing that wastewater can be a source of ARB. Our research focuses on ARB, but as complex a matrix as wastewater is from a microbiological and chemical perspective, SSOs and backups are even more complex with social, political, infrastructure, and public health causes and implications. Addressing the myriad risks inherent from SSOs and backups, and to start working on solutions to this challenge, will require collaborative and coordinated interdisciplinary efforts, now and in the future.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgment

The initial pilot work was supported by the JPB Environmental Health Fellowship Program at the T H Chan School of Public Health of Harvard University; Award ID: 030555-00001. Research reported in this publication was also supported by the National Institute On Minority Health And Health Disparities of the National Institutes of Health under Award Number DP2MD019355. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. This research was also supported by a UMD Grand Challenge Team Grant.

Appendix

Example Household Report Card. The information included does not represent an actual participant sample.

ORCID iDs

Marccus D Hendricks https://orcid.org/0000-0002-1072-100X
Rachel E Rosenberg Goldstein https://orcid.org/0000-0002-8190-9376

References

[1] U.S. EPA National pollutant discharge elimination system (NPDES) (available at: www.epa.gov/npdes/sanitary-sewer-overflows-ssos) (Accessed 15 August 2024)
[2] Pryor R 2024 14 million gallons of sewage overflow spills into Baltimore City waterways *Fox 45 Baltimore* (available at: https://foxbaltimore.com/news/local/14-million-gallons-of-sewage-water-spills-into-baltimore-city-waterways)
[3] Hendricks M D and Van Zandt S 2021 Unequal protection revisited: planning for environmental justice, hazard vulnerability, and critical infrastructure in communities of color *Environ. Justice* **14** 87–97
[4] Portnoy J 2022 Aging infrastructure to blame for E. coli bacteria in Baltimore water (The Washington Post) (available at: www.washingtonpost.com/dc-md-va/2022/09/30/baltimore-water-ecoli-infrastructure/)
[5] Kochtitzky C S *et al* 2006 Urban planning and public health at CDC (MMWR supplements) vol 55 pp 34–38 (available at: https://pubmed.ncbi.nlm.nih.gov/17183243/)
[6] Corburn J 2007 Reconnecting with our roots: american urban planning and public health in the twenty-first century *Urban Aff. Rev.* **42** 688–713
[7] Frank L D and Kavage S 2008 Urban planning and public health: a story of separation and reconnection *J. Public Health Manage. Pract.* **14** 214–20
[8] Corburn J 2004 Confronting the challenges in reconnecting urban planning and public health *Am. J. Public Health* **94** 541–6
[9] Melosi M V 2008 *The Sanitary City: Environmental Services in Urban America from Colonial Times to the Present* (University of Pittsburgh Pre)
[10] Newsom S W B 2006 Pioneers in infection control: John Snow, Henry Whitehead, the Broad Street pump, and the beginnings of geographical epidemiology *J. Hosp. Infect.* **64** 210–6
[11] Cameron D and Jones I G 1983 John Snow, the Broad Street pump and modern epidemiology *Int. J. Epidemiol.* **12** 393–6
[12] McLeod K S 2000 Our sense of Snow: the myth of John Snow in medical geography *Soc. Sci. Med.* **50** 923–35
[13] Paneth N 2004 Assessing the contributions of John Snow to epidemiology 150 years after removal of the Broad Street pump handle *Epidemiology* **15** 514–6
[14] Snow J On the mode of communication of cholera J Churchill and J Tibbetts 2005 *Combined Sewer Systems: Down, Dirty, and Out of Date* (Environmental Health Perspectives) pp A464–A467 1855
[15] Centers for Disease Control and Prevention (CDC) 1999 MMRW weekly (available at: www.cdc.gov/mmwr/preview/mmwrhtml/00056796.htm)
[16] Cutler D and Miller G 2005 The role of public health improvements in health advances: the twentieth-century United States *Demography* **42** 1–22
[17] Campos L C, Ross P, Nasir Z A, Taylor H and Parkinson J 2015 Development and application of a methodology to assess sanitary risks in Maputo, Mozambique *Environ. Urban.* **27** 371–88
[18] U.S. EPA Why control sanitary sewer overflows? (available at: www.epa.gov/sites/production/files/2015-10/documents/sso_casestudy_control.pdf) (Accessed 10 May 2020)
[19] Jagai J S, DeFlorio-Barker S, Lin C J, Hilborn E D and Wade T J 2017 Sanitary sewer overflows and emergency room visits for gastrointestinal illness: analysis of Massachusetts data, 2006–2007 *Environ. Health Perspect.* **125** 117007
[20] Ahmed W, Hamilton K, Toze S, Cook S and Page D 2019 A review on microbial contaminants in stormwater runoff and outfalls: potential health risks and mitigation strategies *Sci. Total Environ.* **692** 1304–21
[21] National Academy of Science 2002 Prioritization of water of services in the us: an assessemnt of issues and experiences (available at: https://nap.nationalacademies.org/read/10135/chapter/1)
[22] U.S. EPA Small and rural wastewater systems (available at: www.epa.gov/small-and-rural-wastewater-systems/about-small-wastewater-systems) (Accessed 12 August 2024)
[23] U.S. EPA National pollutant discharge elimination system (NPDES): combined sewer overflow frequent questions Where are the cities with,have fewer than 10%2C000 people (available at: www.epa.gov/npdes/combined-sewer-overflow-frequent-questions#:[?]:text)
[24] U.S. EPA Combined sewer overflow management fact sheet sewer separation (Office of Water, D.C.) (Accessed 1 March 2020) (available at: www3.epa.gov/npdes/pubs/sepa.pdf)
[25] ASCE *2021 Report Card for America's Infrastructure*
[26] Kessler R 2011 Stormwater strategies: cities prepare aging infrastructure for climate change *Environ. Health Perspect.* **119** a514–9

[27] Goulding R, Jayasuriya N and Horan E 2012 A Bayesian network model to assess the public health risk associated with wet weather sewer overflows discharging into waterways *J. Water Res.* **46** 4933–40
[28] Olds H T, Corsi S R, Dila D K, Halmo K M, Bootsma M J and McLellan S L 2018 High levels of sewage contamination released from urban areas after storm events: a quantitative survey with sewage specific bacterial indicators *PLoS Med.* **15** e1002614
[29] Sauer E P, VandeWalle J L, Bootsma M J and McLellan S L 2011 Detection of the human specific Bacteroides genetic marker provides evidence of widespread sewage contamination of stormwater in the urban environment *Water Res.* **45** 4081–91
[30] Passerat J, Ouattara N K, Mouchel J M, Rocher V and Servais P 2011 Impact of an intense combined sewer overflow event on the microbiological water quality of the Seine River *J. Water Res.* **45** 893–903
[31] Reisinger A J, Woytowitz E, Majcher E, Rosi E J, Belt K T, Duncan J M, Kaushal S S and Groffman P M 2019 Changes in long-term water quality of Baltimore streams are associated with both gray and green infrastructure *Limnol. Oceanogr.* **64** S60–S76
[32] Börjesson S, Matussek A, Melin S and Lindgren P E 2009 A seasonal study of the mecA gene and Staphylococcus aureus including methicillin-resistant S. aureus in a municipal wastewater treatment plant *Water Res.* **43** 925–32
[33] Börjesson S, Matussek A, Melin S, Löfgren S and Lindgren P E 2010 Methicillin-resistant staphylococcus aureus (MRSA) in municipal wastewater: an uncharted threat? *J. Appl. Microbiol.* **108** 1244–51
[34] Goldstein R E R *et al* 2014 Detection of vancomycin-resistant enterococci (VRE) at four U.S. wastewater treatment plants that provide effluent for reuse *Sci. Total Environ.* **466–467** 404–11
[35] Goldstein R E R *et al* 2012 Methicillin-resistant staphylococcus aureus (MRSA) detected at four U.S. wastewater treatment plants *Environ. Health Perspect.* **120** 1551–8
[36] Carey S A, Goldstein R E R, Gibbs S G, Claye E, He X and Sapkota A R 2016 Occurrence of vancomycin-resistant and -susceptible Enterococcus spp. in reclaimed water used for spray irrigation *Environ. Res.* **147** 350–5
[37] Thapaliya D *et al* 2017 Prevalence and characterization of staphylococcus aureus and methicillin-resistant staphylococcus aureus on public recreational beaches in northeast ohio *GeoHealth* **1** 320–32
[38] McLellan S L, Hollis E J, Depas M M, Van Dyke M, Harris J and Scopel C O 2007 Distribution and fate of escherichia coli in lake michigan following contamination with urban stormwater and combined sewer overflows *J. Gt. Lakes Res.* **33** 566–80
[39] Mork R L *et al* 2019 Longitudinal, strain-specific Staphylococcus aureus introduction and transmission events in households of children with community-associated meticillin-resistant S aureus skin and soft tissue infection: a prospective cohort study *Lancet Infect. Dis.* **20** 188–98
[40] Centers for Disease Control and Prevention (CDC) 2019 *Antibiotic Resistance Threats in the United States, 2019* (U.S. Department of Health and Human Services) (https://doi.org/10.15620/cdc:82532)
[41] Gualandi N *et al* 2018 Racial disparities in invasive methicillin-resistant staphylococcus aureus infections, 2005–2014 *Clin. Infect. Dis.* **67** 1175–81
[42] Hassoun-Kheir N, Stabholz Y, Kreft J-U, de la Cruz R, Romalde J L, Nesme J, Sørensen S J, Smets B F, Graham D and Paul M 2020 Comparison of antibiotic-resistant bacteria and antibiotic resistance genes abundance in hospital and community wastewater: a systematic review *Sci. Total Environ.* **743** 140804
[43] Proia L, Anzil A, Subirats J, Borrego C, Farrè M, Llorca M, Balcázar J L and Servais P 2018 Antibiotic resistance along an urban river impacted by treated wastewaters *Sci. Total Environ.* **628–629** 453–66
[44] Skariyachan S, Mahajanakatti A B, Grandhi N J, Prasanna A, Sen B, Sharma N, Vasist K S and Narayanappa R 2015 Environmental monitoring of bacterial contamination and antibiotic resistance patterns of the fecal coliforms isolated from Cauvery River, a major drinking water source in Karnataka, India *Environ. Monit. Assess.* **187** 1–13
[45] Hladicz A, Kittinger C and Zarfel G 2017 Tigecycline resistant Klebsiella pneumoniae isolated from Austrian river water *Environ. Res. Public Health* **14** 1169
[46] Rodríguez-Molina D *et al* 2021 Carriage of ESBL-producing Enterobacterales in wastewater treatment plant workers and surrounding residents—the AWARE study *Eur. J. Clin. Microbiol. Infect. Dis.* 1–16
[47] Berglund F *et al* 2023 The resistome and microbiome of wastewater treatment plant workers—the AWARE study *Environ. Int.* **180** 108242
[48] Wengenroth L *et al* 2021 Antibiotic resistance in wastewater treatment plants and transmission risks for employees and residents: the concept of the AWARE study *Antibiotics* **10** 478
[49] Kumar M *et al* 2022 Lead time of early warning by wastewater surveillance for COVID-19: geographical variations and impacting factors *Chem. Eng. J.* **441** 135936