Communication

Looking Forward: The Role of Academic Researchers in Building Sustainable Wastewater Surveillance Programs

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Abstract: Background: In the span of just two years, tracking the COVID-19 pandemic through wastewater surveillance has advanced from early reports of successful SARS-CoV-2 RNA detection in untreated wastewater to implementation of programs in at least 60 countries. Early wastewater monitoring efforts primarily originated in research laboratories and are now transitioning into more formal surveillance programs run in commercial and public health laboratories. A major challenge in this progression has been to simultaneously optimize methods and build scientific consensus while implementing surveillance programs, particularly during the rapidly changing landscape of the pandemic. Translating wastewater surveillance results for effective use by public health agencies also remains a key objective for the field. **Objectives:** We examine the evolution of wastewater surveillance to identify model collaborations and effective partnerships that have created rapid and sustained success. We propose needed areas of research and key roles academic researchers can play in the framework of wastewater surveillance to aid in the transition of early monitoring efforts to more formalized programs within the public health system. **Discussion:** Wastewater surveillance has rapidly developed as a public health tool. Clinical testing programs are ramping down and home testing is on the rise, making wastewater monitoring important for future surveillance of COVID-19. Our experience in initiating and implementing wastewater surveillance programs in the United States has allowed us to reflect on key barriers and organizational challenges and draw useful lessons. As wastewater surveillance programs are formalized, the working relationships developed between academic researchers, commercial and public health laboratories, and data users should continue and should promote knowledge co-development. While wastewater surveillance has demonstrated utility for tracking COVID-19, there remain technical challenges and open scientific questions that researchers are equipped to address, which will contribute to building robust surveillance programs that provide public health practitioners with new insights into population health.

Keywords: Covid-19; SARS-CoV-2; Wastewater; research; surveillance

Introduction

In the midst of the COVID-19 pandemic, SARS-CoV-2 wastewater surveillance has gained traction globally as a means to assess the occurrence of infections in communities. Shortly after the first reported detection of SARS-CoV-2 RNA in wastewater in the

Netherlands, the virus was detected in untreated sewage in several countries, including the US, Australia, and India (Ahmed et al. 2020a; Kumar et al. 2020; Medema et al. 2020; Sherchan et al. 2020), indicating that the virus' genetic material was sufficiently abundant in wastewater to provide a reliable indication of community infections. Efforts shifted from basic detection to attempts to quantify and characterize the relationship between SARS-CoV-2 RNA in wastewater and associated COVID-19 clinical case data (Graham et al. 2020; Peccia et al. 2020). Methodologies were refined to provide more quantitative grounding for wastewater measurements (Pecson et al. 2021; Philo et al. 2021). Academic researchers in environmental engineering, environmental science, microbiology, and similar fields were heavily engaged in these efforts and disseminated early information to demonstrate the promise and challenges of wastewater surveillance for population-level assessments of infection. This included many channels of communication such as published manuscripts and preprints, an NSF-funded Research Coordination Network (Reseach Coordination Network), workshops, collaboratives, and informal communications, with knowledge shared freely across the scientific community.

As the pandemic progressed, wastewater surveillance efforts became more widespread, particularly in the US, with many major cities as well as some rural areas implementing programs (Naughton et al. 2021). Research entities, including many universities, often led or participated in these efforts, in large part due to the need to overcome challenging method development alongside implementation of wastewater surveillance programs. This allowed for rapid implementation during a time of great need, but there were challenges in interpretation and potential actionability of the data. Academic researchers were not always experienced with how decision making occurs within public health systems. Public health practitioners were also challenged with assessing a new data stream that is distinct from traditional disease incidence metrics, such as tracking hospitalizations or clinical test positivity rates (McClary-Gutierrez et al. 2021). Researchers with expertise producing and interpreting environmental data and public health practitioners with expertise in outbreak response approached wastewater surveillance with distinct knowledge bases, different definitions for key terms like "variability" and "uncertainty", and at times different priorities (e.g., improving science-based measurements vs. implementing public health measures). Close working partnerships were critical in bridging this gap, and wastewater surveillance has now matured into a useful tool for COVID-19 outbreak response and has been prioritized by the Centers for Disease Control and Prevention (Kirby et al. 2021) and some states as part of future public health response.

As the pandemic evolves and moves to an endemic phase, there is a need to sustain wastewater surveillance programs for SARS-CoV-2 as well as further develop methods for other pathogens of concern (Kirby et al. 2021). Here, we provide a perspective on the shifting role of researchers from data generators to supporting partners of wastewater surveillance programs, discuss important lessons learned from implementing these programs, and identify key activities that researchers can engage in to contribute to the long-term utility of wastewater surveillance as a public health tool.

Discussion

Evolution of SARS-CoV-2 wastewater surveillance from research to practice

Many early SARS-CoV-2 wastewater surveillance efforts were initiated by academic researchers in collaboration with public health, wastewater, or municipal partners (Bivins et al. 2020; Graham et al. 2020; Randazzo et al. 2020; Sherchan et al. 2020). The environmental microbiology capacity and experience of academic research labs positioned them to respond effectively to develop the analytical methods required for processing a complex sample matrix for wastewater monitoring. By developing methods and beginning regular sample processing, academic research labs were instrumental in starting wastewater surveillance programs in US cities such as Houston, Texas, and San Francisco and San Diego, California, USA, and statewide programs in Utah, Wisconsin, and Ohio,

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USA (Ai et al. 2021; Feng et al. 2021; Greenwald et al. 2021; Karthikeyan et al. 2021b; Laturner et al.; Weidhaas et al. 2021; Wolfe et al. 2021). The structure of these partnerships varied, but in many instances, municipal utilities facilitated sample collection and logistics, and academic partners managed the analytical burden, developing methodologies, processing samples, and providing data interpretation for public health partners, who then could use the information for decision making (Feng et al. 2021; Graham et al. 2020; Laturner et al. 2021; Whitney et al. 2021). Such arrangements were pragmatic given the urgency and rapidly evolving nature of the pandemic. In other situations, public health, municipal utility, or other government agencies were responsible for some or all aspects of surveillance (Gerrity et al. 2021; Gonzalez et al. 2020; Hoar et al. 2022; Nagarkar et al. 2022). Other research programs focused more strictly on method development and fundamental explorations that would be useful to the broader scientific community without explicitly identified partner recipients (Bivins et al. 2021; Pecson et al. 2021; Philo et al. 2021). A number of private companies have also emerged as providers of wastewater surveillance services, from sample testing to data analysis and reporting.

While wastewater surveillance at treatment plants can provide community-level insights into COVID-19 trends, another application is to monitor for SARS-CoV-2 RNA in wastewater collected from smaller areas or individual buildings. College campuses, for example, have been particularly well-suited for this type of localized wastewater surveillance, with efforts reported on at least 25 campuses in the United States (Harris-Lovett et al. 2021). In several cases, surveillance teams have been able to use wastewater data to reportedly avert COVID-19 outbreaks among populations in large residential halls (Betancourt et al. 2021; Brooks et al. 2021; Corchis-Scott et al. 2021). Efforts on university campuses have spanned the methodological gradient, from large-scale composite sampling and high-throughput automated analysis to greatly simplified passive sampling with qualitative RT-LAMP testing (Bivins et al. 2022; Karthikeyan et al. 2021a; Reeves et al. 2021). For these reasons, universities have proven to be an important testbed for wastewater surveillance of SARS-CoV-2 infections among defined populations.

Throughout the evolution of COVID-19 wastewater surveillance thus far, a progressively larger group of public health practitioners have utilized wastewater data (Kirby et al. 2021). In the early stages of the pandemic, some members of the public health community were hesitant regarding the use wastewater data for decision making as wastewater data was unfamiliar and its performance characteristics were largely unknown (Ahmed et al. 2020b, 2022; McClary-Gutierrez et al. 2021; Water Research Foundation 2020). Efforts to define uncertainty in the wastewater data as well as understand its relationship to clinical case data (Feng et al. 2021; Wolfe et al. 2021) continue to build confidence and improve potential for application. In addition, as practitioners gained experience and a larger knowledge base was generated, deploying a national wastewater surveillance system for COVID-19 seemed increasingly feasible (Keshaviah et al. 2021; Sharara et al. 2021).

As states implement their programs, contributions of their data to such a system offers a nationwide comparison of wastewater surveillance data and a community of practitioners to share methods and experience. Critical to these efforts has been funding to states to establish programs. In September 2020, the CDC launched the National Wastewater Surveillance System (NWSS) in the US, and on February 4, 2022, wastewater data were officially incorporated into the agency's COVID-19 Data Dashboard (Centers for Disease Control and Prevention). Globally, countries such as the Netherlands, UK, Austria, Australia, Canada, Pakistan, Malawi, and Spain (to name a few) have national and regional dashboards showing wastewater surveillance results (Global Water Pathogens Project). There are an increasing number of examples showing that, if performed in the context of a well-organized and well-integrated effort, wastewater surveillance can aid public health responses (Global Water Pathogens Project; Safford et al. 2022).

Looking back: Lessons learned

In our experience, the most important aspect of successful wastewater surveillance programs thus far has been the development of multi-stakeholder partnerships founded in active collaboration and communication throughout the process. As researchers in academic laboratories, we have historically worked with a broad array of partners in university administration, municipalities, industry, and public health laboratories; these foundational relationships allowed us to quickly expand or initiate new collaborations to start wastewater surveillance programs. Our partnerships have taken many forms, and here we discuss some of the lessons learned from these different types of collaborations (**Box 1**).

One effective model for cooperation involved direct partnerships between academic researchers and public health laboratories, many of which are members of the Association of Public Health Laboratories (APHL). These partnerships, by nature, extended to the environmental health or public health departments that the laboratories serve and allowed wastewater surveillance efforts to tap into existing frameworks for communication and data transfer within the public health system. Researchers in these partnerships brought specific technical and scientific expertise that helped implement virus detection in the complex matrix of wastewater, which added to the capacity of public health laboratories to expand testing to include untreated sewage. We found that environmental health experts within public health departments were often effective liaisons between the data producers and data end users because of their familiarity with both environmental measurements and clinical data (McClary-Gutierrez et al. 2021). In addition, some state public health laboratories are housed within universities and thus have existing collaborative research with academic units. With this model, academic researchers, students, and postdoctoral scholars were able to use their existing expertise to focus on thoroughly investigating scientific and technical questions without detracting from the routine analysis pipeline. In addition, public health laboratories had the capacity to scale up and optimize methods using high-throughput platforms. Ongoing exchange of information allowed each partner to stay apprised of the latest developments in the field more easily. Collective troubleshooting and sample exchange for cross validation were also beneficial for accelerated data interpretation.

It is noteworthy that several of the seven states that were the first and are currently the largest participants in the NWSS had academic research/public health laboratory partnerships early in the pandemic (Centers for Disease Control and Prevention). In Wisconsin, a partnership between a research laboratory and the state public health laboratory, also part of a university, enabled the implementation of a statewide wastewater surveillance program (State of Wisconsin) with 72 WWTPs in August 2020 (Feng et al. 2021). The statewide wastewater surveillance program in Illinois is similarly organized, with a partnership between a university, and city and state public health entities. The Illinois program began in October 2020 with 7 WWTPs in the City of Chicago (City of Chicago) and expanded statewide in May 2021 with 65 WWTPs in 49 counties (Illinois) (Owen et al.). The Ohio and Utah statewide programs are additional examples of this type of partnership (Kirby et al. 2021).

Academic researchers also collaborated with other types of laboratories to build capacity for surveillance programs, including municipal wastewater utility laboratories and commercial laboratories capable of rapid, high-throughput sample processing (Hoar et al. 2022; Wolfe et al. 2021). In both cases, academic researchers were involved in methods development, data analysis, and troubleshooting, but routine analysis was conducted by a dedicated staff of analysts using agency or company staffing logistics (i.e., shifts, overtime policies) that are not often established in academic labs. We found that engaging such laboratory partners (whether municipal or commercial) from the beginning of protocol optimization allowed academic partners to train analysts as needed and incorporate feedback from analysts and scientists who offered important perspectives into practical and scientific considerations for routine sample processing. Working directly with municipal

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laboratories associated with wastewater utilities offers the logistical benefits of using existing sample collection and transport structures and having direct access to wastewater data (e.g., wastewater flow rates and characteristics) critical for troubleshooting and data interpretation. Partnering with commercial laboratories offered the benefit of using existing equipment, leveraging expertise of personnel, and applying existing high-throughput sample processing strategies.

Finally, some academic researchers worked solely in their own laboratories to generate data without a specific data end-user identified. While in these instances the resulting data were not used in real time, findings from these efforts have been critical in establishing the scientific basis for wastewater surveillance, including proof-of-concept and method development, and will be important for retrospective analysis in local areas moving forward. All of these early frameworks offered a platform for cooperative research to refine and validate methods.

Regardless of whether or not public health practitioners are directly involved in data generation, close collaboration among researchers, public health agencies, and laboratories with the capacity to handle an increasing number of samples is critical for sustaining programs. Sustaining high throughput sample processing has been a challenge for academic laboratories operating under some of the early frameworks described above. As wastewater surveillance becomes more established, commercial laboratories may therefore fill a needed niche for high-throughput sample processing, with integrated expertise from public health and academic partners to facilitate interpretation of resulting data in a public health context.

Box 1: Lessons learned: what worked and what did not when establishing wastewater surveillance

What worked

- Creating partnerships between academic research and public health laboratories
- Leveraging high throughput capacity of commercial, municipal, or public health laboratories with researchers providing hands on involvement in optimizing and validating protocols
- Cross training and exchange of laboratory personnel between research and public health labs
- Providing advice and guidance to partners to design and execute program and work towards sustainable operations

What did not work

- Scaling up processing in academic labs without a long-term plan for transfer to a production lab
- Missing partners at the table (WWTP, public health end users)
- Not identifying data recipients at the beginning of the effort
- Providing data without access to expertise to explain the context, scientific basis, limitations, and interpretations

Looking forward: Role of academic researchers in wastewater surveillance

The evolution of wastewater surveillance during the COVID-19 pandemic has demonstrated the utility of wastewater surveillance programs during disease outbreaks and underscored the need for dynamic, collaborative program structures to respond to rapidly changing circumstances. Specifically, wastewater surveillance programs require expertise from multiple disciplines, as well as reliable and reproducible methodologies, capacity in both supplies and trained personnel, expertise in interpretation of the data, and ability to efficiently pivot efforts to address new priorities while combatting evolving outbreaks. As wastewater surveillance programs become integrated into public health

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systems, continued access to scientific expertise in engineering and microbiology will be crucial in establishing wastewater surveillance as an effective, institutionalized public health tool. There are three interconnected activities that are essential for the support of effective wastewater surveillance systems, namely (1) pioneering new capabilities, (2) sustaining surveillance efforts, and (3) integrating surveillance data for effective public health response (**Figure 1**). Academic researchers can play an important role in contributing to each of these activities.

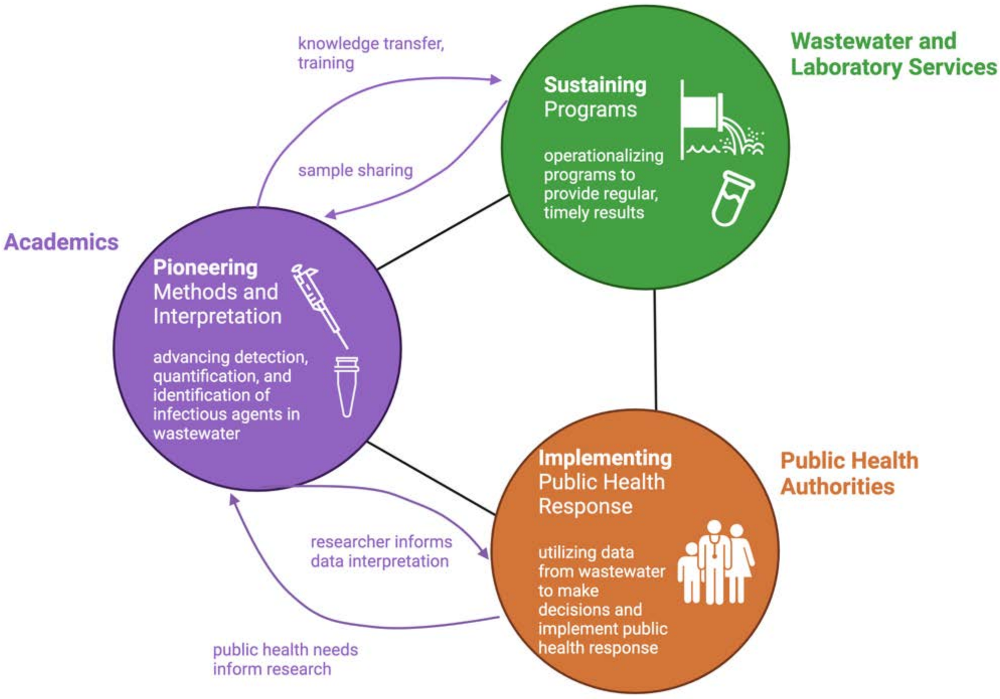

Figure 1. Framework for building robust and adaptive wastewater surveillance programs. In addition to undertaking basic research that underpins the basis of wastewater surveillance, researchers have a critical role to play in continuous methods development, technology transfer, research that informs data context and interpretation, and training the next generation of professionals.

Pioneering new capabilities

Even as wastewater surveillance becomes more routine, infectious agents by their nature are constantly evolving. A primary role researchers should play in the future of wastewater surveillance will be pioneering new capabilities and methods for detection, quantification, and identification of infectious agents in wastewater, and interpretation of the relationship between resulting data and health outcomes (**Table 1**). Thus far, the COVID-19 pandemic has demonstrated that both existing public health metrics and novel techniques are critical for our ability to respond to and stay ahead of emerging public health crises. A clear example of this has been in the identification and rapid roll-out of new assays for identifying SARS-CoV-2 variants of concern. Researchers designed new assays for the SARS-CoV-2 Omicron variant within a few days of its identification, and wastewater surveillance programs in four states (California, Colorado, New York, and Texas) were able to use these assays and sequencing-based approaches to detect evidence of the Omicron variant within days of the first clinical cases, demonstrating in some areas that the variant was already spreading in the community before clinical cases were identified (Kirby et al. 2022).

Before SARS-CoV-2, wastewater surveillance was used to study the epidemiology of a variety of infectious diseases, although these were most often fecal-oral pathogens. Most famously, wastewater has been used to study the epidemiology of poliovirus and other enteroviruses (Bondarenko et al. 1991; Manor et al. 1999; Ozere et al. 1961; Peigue-Lafeuille et al. 1985), and many other infectious agents have been surveilled via wastewater including *Vibrio cholerae*, hepatitis E, *Cryptosporidium*, group A rotavirus, norovirus, and *Giardia*, to name a few (Madico et al. 1996; Pina et al. 1998; Robertson et al. 2008; Sedmak et al. 2003; Villena et al. 2003; Zhou et al. 2003). The recent success of wastewater surveillance for SARS-CoV-2 is now rekindling interest in using wastewater to examine the epidemiology of other respiratory viruses such as respiratory syncytial virus (RSV) and influenza A (Hughes et al. 2022; Wolfe et al. 2022b). Expanding the wastewater surveillance paradigm to include a diversity of infectious agents, along with a fundamental characterization and mechanistic understanding of these pathogens' fate and transport in wastewater, will continue to be a crucial pioneering contribution of research teams.

As the COVID-19 pandemic enters an endemic phase and infections in the community decrease, more sensitive methods will be needed. Researchers can play an important role in developing these new, more sensitive methods. For example, early in the COVID-19 pandemic, researchers found wastewater solids to be an efficient and methodologically convenient SARS-CoV-2 sample type (D'Aoust et al. 2021; Graham et al. 2020; Kim et al. 2022; Peccia et al. 2020). Other research teams have also made use of suspended solids as a highly sensitive approach to wastewater surveillance, even during periods of low transmission or after mass vaccination (e.g., on a university campus) (Bivins and Bibby 2021; Wolfe et al. 2021). Sensitive methods will also be needed for new infectious disease targets that may not be as prevalent as SARS-CoV-2. While solids have been found to be useful for SARS-CoV-2 and could also be useful for other targets, other viruses, or bacterial or fungal targets, may behave differently in wastewater depending on their morphology and structure , and so continuing methods development is important for new pathogens (Ye et al. 2016).

In the future, scaling-up wastewater surveillance programs and efforts to make wastewater surveillance programs more widely accessible will also require the development of methods that are cost-efficient and less resource intensive. Here researchers will also continue to play a strategic role, as exemplified by currently published research efforts. Various research teams have led efforts to develop passive sampling techniques, such as the Moore swab, for economical sampling of wastewater with superior performance to grab sampling (Habtewold et al. 2022; Hayes et al. 2022; Liu et al. 2022). In addition, researchers have also initiated efforts to develop molecular testing techniques that do not require expensive quantitative PCR equipment, such as loop-mediated isothermal amplification (LAMP) (Amoah et al. 2021) and have coupled these with passive samplers and electronegative membranes to allow rapid wastewater testing (Bivins et al. 2022; Zhu et al. 2022). Researchers have also proposed paper-based testing devices and biosensors as future analytical platforms for near real-time surveillance of infectious agents in wastewater, although as of yet no proof of concept has been published (El-Sherif et al. 2022). It is abundantly clear that researchers have many contributions to make in the development of efficient and scalable wastewater surveillance methodologies.

Outside of laboratory method development, there remains a critical need to continue advancing modeling and data analysis methods for wastewater surveillance applications. Early efforts during the COVID-19 pandemic relied on relatively simple correlation analyses between SARS-CoV-2 RNA concentrations and COVID-19 cases or hospitalizations in a community. As research efforts continue to develop numerical techniques for surveillance of SARS-CoV-2 and other targets, continued attention on predictive modeling techniques and integration of wastewater data into other epidemiological data analyses will remain critical. Further, retrospective analyses of the volumes of data that have been collected during the COVID-19 pandemic may reveal important insights into that will inform our response to future pandemics.

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Table 1. Pioneering activities for strategic engagement of academic researchers to advance wastewater surveillance.

Pioneering Research Activity	Published Examples
Surveillance of new SARS-CoV-2 variants of concern and lineages	Wastewater surveillance of alpha variant (B.1.1.7) via spike protein mutations detected in wastewater in the United Kingdom (Carcereny et al. 2022) Screening for alpha (B.1.1.7), beta (B.1.351), and gamma (P.1) variants of concern via RT-qPCR allelic discrimination assays (Peterson et al. 2022) Rapid response wastewater surveillance of omicron variant (B.1.1.529) throughout the United States (Kirby et al. 2022; Wolfe et al. 2022a; Yu et al. 2021) Genomic sequencing of SARS-CoV-2 from wastewater to monitor variants of concern (B.1.1.7, B.1.351, B.1.617.2) in municipalities across Europe (Agrawal et al. 2022) Wastewater surveillance of SARS-CoV-2 lineages via deep sequencing of the receptor binding domain (Smyth et al. 2022)
Method development, refinement, and optimization	Kit-free RNA extraction method for wastewater surveillance of SARS-CoV-2 (Whitney et al. 2021) Rapid, high-throughput wastewater testing via automated concentration and extraction (Karthikeyan et al. 2021a) (Karthikeyan et al., 2021) Monitoring of SARS-CoV-2 via wastewater settled solids (Graham et al. 2020; Wolfe et al. 2021) Biosensors for near real-time wastewater surveillance (Mao et al. 2020)
Development of resource-efficient methods for accessible wastewater surveillance	Passive sampling and RT-LAMP for building-level wastewater surveillance (Bivins et al. 2022) Membrane-based RT-LAMP for wastewater surveillance of SARS-CoV-2 (Zhu et al. 2022) Paper-based testing devices for wastewater surveillance
Biological analyte fate and transport in wastewater systems	SARS-CoV-2 accumulation in biofilms in wastewater collection systems (Morales Medina et al. 2022) Enhanced decay of SARS-CoV-2 RNA in sewers with biofilms (Shi et al. 2022) Partitioning of enveloped and unenveloped viruses to suspended solids (Ye et al. 2016)
Wastewater surveillance of other infectious agents	Respiratory syncytial virus surveillance via wastewater settled solids (Hughes et al. 2022) Deep sequencing of wastewater for enterovirus surveillance (Bisseux et al. 2020) Influenzae wastewater surveillance (Wolfe et al. 2022b)
Modeling and quantitative analysis	Distributed-lag time series model to relate SARS-CoV-2 RNA counts in sewage and COVID-19 cases (Peccia et al. 2020) Susceptible-exposed-infected-recovered model to relate SARS-CoV-2 RNA counts in wastewater and prevalence of COVID-19 (McMahan et al. 2021)

Sustaining surveillance efforts

Similar to other public or environmental health monitoring efforts, effective wastewater surveillance requires frequent sample collection and analysis. Many researchers have determined that a minimum frequency of weekly or biweekly sampling is needed for useful applications of the data (Feng et al. 2021; Graham et al. 2020) and daily samples with 24-hour turnaround are ideal in some use cases (personal communication). Despite the efforts that research labs have undertaken to initiate wastewater surveillance programs during the pandemic and the value that these efforts have had in technical training and education (Delgado Vela et al. 2022), it is also clear that research labs cannot be expected to sustain the day-to-day sampling, analysis, and monitoring required by full-fledged, long-term surveillance systems – nor should they. Research labs typically work on novel solutions to both new and long-standing challenges and, in academic settings, are meant to provide a training ground for students and early career scientists to develop their critical thinking, experimental research, and professional skills. Public health labs and commercial labs are, on the other hand, well suited for routine analyses and data production, given their high-throughput capacity, technical expertise, and existing personnel management structures.

In instances where academic labs have taken active roles in generating wastewater surveillance data during the first years of the COVID-19 pandemic, these responsibilities will need to switch to either the end users of the data (public health labs/municipalities) or to other high-production entities (commercial labs). This necessary shift from routine monitoring in research labs to professional labs does not, however, imply that researchers will not have a critical role to play in the sustainability of surveillance efforts. Wastewater surveillance is a highly interdisciplinary area, and the professional skillsets required to sustain these efforts are widely distributed across a range of fields, including environmental engineering, microbiology, molecular biology, statistics, epidemiology, data management, public policy, and data communication, among others (Table 2). Researchers will need to play a key role in transferring and combining these skillsets in the professional world through training, sharing expertise, and technology transfer of new methods.

Table 2. Examples of disciplines and skills required for effective wastewater surveillance programs.

Disciplines	Skills
Environmental Engineering	- sewer system design - sample collection logistics - fate & transport of sewer organisms
Environmental Microbiology & Molecular Biology	- environmental sample processing methods - molecular detection techniques - sample data interpretation
Statistics & Data Science	- trend and correlation analyses - large data-set management - predictive modeling
Public Health & Public Policy	- epidemiological modeling - intervention strategies - policy development
Communication	- infographic design - science communication to public audiences - community and political coordination

Professional laboratories are likely the most appropriate landing place for wastewater surveillance efforts, and as such will require specialized skillsets and interdisciplinary collaborations. For example, wastewater as a matrix is highly complex and unique in comparison to the types of sample materials typically worked with in clinical laboratories (e.g., blood or fecal specimens), and methods for optimal wastewater processing remain unstandardized. Because of this, one of the most critical roles for researchers is training the next generation of students who will in turn sustain long-term wastewater surveillance efforts as they enter the workforce. By professionalizing the discipline of wastewater surveillance through formal and informal educational and training programs, researchers can also benefit from permanent relationships with monitoring programs and professional labs that allow rapid identification of new research questions and areas for improvement.

Despite the routine nature of wastewater surveillance programs, the constant evolution of the COVID-19 pandemic has and will continue to require efficient responses to major changes in the pandemic trajectory. As the transition to a sustainable wastewater surveillance infrastructure continues, researchers can in the short-term continue to support these programs by consulting on data interpretation, methodological improvements as discussed previously, and other specialized areas. As more functions and capabilities become routine among professional labs, the consulting role of researchers will likely decrease through creation of a professional career path and development of institutional

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knowledge. Nonetheless, researchers can and should be called upon to offer their expertise when circumstances require shifts or adoption of new capabilities.

Integrating surveillance data for effective public health response

An important goal of wastewater surveillance programs is to monitor outbreaks to inform public health actions. As wastewater surveillance programs expanded to achieve this goal, close partnerships and knowledge sharing between academics involved in project implementation and public health practitioners in a position to use data for pandemic response were essential. Because the field progressed quickly, there was a significant need for researchers to act as conduits to public health agencies to provide information on the scientific basis for the measurements, the limitations and uncertainty, and how that data could be contextualized and interpreted.

In Houston, wastewater surveillance efforts have been led by public health experts, and results have been used to target testing, vaccination, and educational resources toward parts of the city with particularly high COVID-19 burden identified via wastewater samples. In several cases, wastewater testing conducted on campuses by academic institutions has been used by those institutions to implement additional targeted testing and other responsive measures to protect public health (Betancourt et al. 2021; Karthikeyan et al. 2021a; Scott et al. 2021). City-wide testing can also inform decisions such as mask mandates and hospital staffing and resource forecasting as a new outbreak begins (Kirby et al. 2021).

The novelty of wastewater monitoring and ongoing adaptations to meet evolving needs during the COVID-19 outbreak and beyond can be aided by researcher-practitioner partnerships that facilitate changes to ongoing programs and development of public health guidelines based on these conclusions. Practitioners and researchers should acknowledge that what is knowable from wastewater surveillance has and will continue to change as the technology develops. One key example is the surveillance of SARS-CoV-2 variants in wastewater. Although technical challenges originally raised concerns about the feasibility of this use case, variant tracking through wastewater has proven valuable to provide indicators of variants in circulation – in some cases ahead of clinical data – despite important technical caveats (Kirby et al. 2022; Schussman et al. 2022; Wolfe et al. 2022a). Researchers who have pioneered new techniques have an important role to guide these advances as they are incorporated into regular operation of wastewater surveillance programs.

As wastewater surveillance is professionalized and other methods of tracking COVID-19 outbreaks relax, data from wastewater will have an even greater role to play in guiding response. In the United States, free testing programs have been discontinued in some places, there is a greater reliance on at-home tests (which are often not reported to authorities), and CDC risk guidelines are based more heavily hospitalization data. This means that wastewater surveillance is less duplicative of other sources of information on outbreaks and has a significant lead on other indicators such as hospitalizations for which reporting will continue to be robust. Researchers should continue to facilitate the interpretation and integration of this new data stream into public health response to outbreaks.

Conclusions

The academic research community launched wastewater surveillance as a largely ad hoc grass roots effort in the face of a global crisis, which in the US has evolved into the National Wastewater Surveillance System. Similar efforts emerged in tandem worldwide (Naughton et al. 2021). Academic research laboratories can and should continue to contribute to these efforts by offering their strengths in pioneering new methods, transferring knowledge and expertise to support data interpretations, and training the next generation of professionals that will work in the frontline agencies involved in wastewater surveillance. Further, academic researchers can contribute to modeling and synthesizing the large volumes of data generated during the first years of the COVID-19 pandemic, which will be critical for understanding future pandemics.

The science and methods behind wastewater surveillance have made steady progress in just over two years, but as a field, it is premature to codify and scale a single method or approach. It is clear there is much work to be done. The rich diversity of methods developed and investigative approaches that spurred the progress to date should continue in academic research labs. Researchers can also contribute to evaluating options for standard methods. As academic researchers shift their efforts towards a more investigative and supporting role, they will have increased bandwidth to tackle important underpinning questions that will make wastewater surveillance, as a population health metric, a more useful tool for the public health community.

The pandemic has prompted many academic researchers to partner with commercial, municipal, and public health laboratories and deliver data and, importantly, key interpretations of that data to the public health sector. We encourage researchers to maintain these connections. There is a distinct advantage for advancing the field if researchers are closely tied to actual surveillance programs, as this provides improved access to samples and data and makes new findings rapidly available for advancing wastewater surveillance. Importantly, two-way communication with public health laboratories and practitioners will foster stakeholder-driven research in academics' programs (see Figure 1).

Researchers will therefore need to make concerted efforts to develop relationships outside of their traditional disciplinary silos. Such efforts are not necessarily motivated by conventional metrics of academic success (i.e., publication of peer-reviewed literature), underscoring the need for new ways to incentivize the continued involvement of researchers in wastewater surveillance programs. Paramount to further advances in the field is funding to pursue research to address the most relevant stakeholder driven questions. Relationships are the impact-limiting ingredient for establishing a new complex public health monitoring system, and it will be important for researchers to stay embedded in the process.

Our proposed model for working partnerships is one in which researchers provide training and consulting, as well as transfer new knowledge from their research programs. The global pandemic organically grew a new type of hands-on academic/public health partnership that accelerated implementation of wastewater surveillance as a public health measure, and we should build upon this success.

Conflicts of interest: The authors have on conflicts of interest to declare

Acknowledgments: We would like to thank Alexandria Boehm for insightful discussions. This work was funded through a grant from the Alfred P. Sloan Foundation.

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