Wastewater Monitoring Raises Privacy and Ethical Considerations

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Abstract— Analysis of municipal wastewater, or sewage for public health applications is a rapidly expanding field aimed at understanding emerging epidemiological trends, including human and disease migration. The newly gained ability to extract and analyze genetic material from wastewater poses important societal and ethical questions, including: How to safeguard data? Who owns genetic data recovered from wastewater? What are the ethical and legal issues surrounding its use? In the U.S., both corporate and legal policies regarding privacy have been historically reactive instead of proactive. In wastewater-based epidemiology (WBE), the pace of innovation has outpaced the ability of social and legal mechanisms to keep up. To address this discrepancy, early and robust discussions of the research, policies, and ethics surrounding WBE analysis and genetics is needed. This paper contributes to this discussion by examining ownership issues for human genetic data recovered from wastewater and the uses to which it may be put. We focus particularly on the risks associated with personally identifiable data, highlighting potential risks, relevant privacy-enhancing technologies, and appropriate ethics. The paper proposes an approach for people conducting WBE studies to help them systematically consider the ethical and privacy implications of their work.

Keywords— wastewater-based epidemiology, sewage, wastewater, genetic, privacy-enhancing technologies, personally identifiable data, ethical and privacy framework.

I. INTRODUCTION

The COVID-19 pandemic of 2020 reminds us that public health is an international issue, affected by globalization, urbanization, and population increase. Since the 1950s, urban living grew from 30% of the world's population to over 50% now and is projected to reach 80% by 2050 [1], [2]. The increasing concentration of people in cities, together with recent technology advances, has stimulated work in wastewater-based epidemiology (WBE), which can potentially provide valuable data to policymakers, researchers, and healthcare professionals, economically and quickly.

Recent advances in WBE have provided methods for extracting new kinds of information from wastewater. For example, scientists today can track viral movement through a city [3], [4], identify hot spots of opioid use [5], or even determine the genealogy of individuals residing in the city, otherwise known as their haplogroup makeup [6]. As methods, algorithms, and applications continue to expand, privacy and ethical considerations are quickly increasing in importance.

Today, pathogens can be surveilled in wastewater; and it is not difficult to imagine tracking other information, such as human movement, in the near future. Without proper attention to key issues, e.g., privacy, tomorrow's cities could easily become the epicenter of surveillance societies [7]. As WBE expands to incorporate emerging genetics research, now is the time to consider the ethical, societal, and privacy concerns of such practices.

This paper reviews current research in WBE and genetic privacy to highlight some of the implications. We review WBE ethics, policies, and genetic data privacy, discussing and proposing technological solutions at the confluence of genetics and wastewater-based epidemiology. Currently, no framework exists to address the evolving technology. We introduce a framework for researchers, organizations, policymakers, and practitioners to consider as the dynamic state of wastewater analysis evolves. The goal of the framework is to preempt emerging ethical and privacy concerns.

II. WASTEWATER-BASED EPIDEMIOLOGY

The emerging field of wastewater-based epidemiology (WBE) examines chemicals and biomarkers from wastewater treatment plants (WWTPs) to study human health. The science involves collecting wastewater from WWTPs and applying analytical chemistry techniques to discover chemical and biological compounds in wastewater [9]. Although this field goes by many names in the scientific research community –
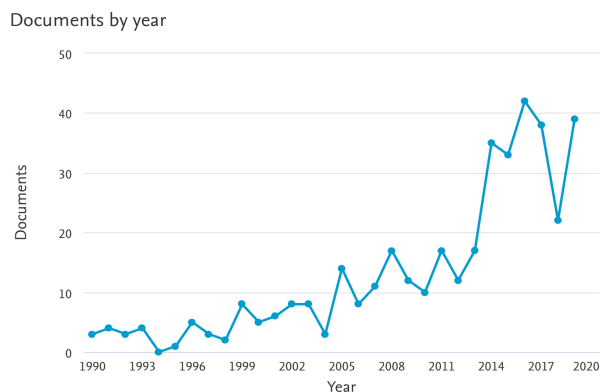
Fig. 1. Publication trends in WBE excerpted from Scopus for the years 1990 to 2019 using the search terms: wastewater-based epidemiology OR wastewater analysis OR wastewater epidemiology [8].

WBE, wastewater analysis (WA), sewage-based epidemiology, and sewage epidemiology [10] – a key focus is the study of trends in human health. What constitutes this human health research is only limited by the compounds found in the wastewater and the epidemiological health questions asked. Historically, wastewater studies originated in the environmental sciences and considered contaminants and pollutants in runoff. However, it quickly evolved into a non-invasive, population-scale method for acquiring information on human activities [11], [12], [13]. In WBE, one popular area is assessing drug use across a population. This field has grown almost exponentially, as shown in Fig. 1. Over time, interest has expanded to include antibiotics, antibiotic-resistant bacteria, and even the leading global public health threat of 2020: SARS-CoV-2 [3].

Although historically there has been less use of WBE in the U.S. than in Europe and Australia [14], this is changing [15], [16]. The popularity and research activity of this science is expanding rapidly [3]. WBE is appealing because critical public health data can be collected quickly and would otherwise require months to collect. In a recent study of samples collected from 13,940 major U.S. city treatment plants, Hart and Halden [16] found distinct geographic demographics that are linked to health. Another study by Hart and Halden [3] applied wastewater analysis to SARS-CoV-2 detection. They used computational simulations to demonstrate the feasibility of identifying a single infected individual by analyzing community wastewater containing samples from 2,000,000 contributing, non-infected persons. Randazzo *et al*. [4] analyzed sewage samples from the Valencian Region of Spain and found cases of SARS-CoV-2 infection in the region a week before cases were reported and a month before the lockdown measures were imposed. These results suggest that WBE can provide critical public health information more quickly than current approaches.

WBE is an appealing approach to public health monitoring because it is inexpensive to collect and analyze biological and chemical data from wastewater. Because it is a critical tool for decision makers, stakeholders have been concerned about the ethics and standards. Lancaster *et al*. [12] present an extensive social science, drug policy, and WBE review using post-structural analysis which examines how WBE incorporates often biased institutional assumptions. For example, when applied to policy there is a presumption that data can create an accurate and complete picture of public health, but this undermines measurement uncertainties in wastewater analysis. The cited paper also reviews the impact that implicit assumptions can have on policy decisions, finding that some institutionalized beliefs require reflection, such as the relationship between socioeconomic status and the local waste treatment plant.

Other papers explore ethical concerns beyond the context of policy and the use of social-science post-structural analysis. In 2012 Hall *et al*. [11] considered the ethical dilemmas faced by WBE researchers. They highlight how WBE could cause stigmatization of particular populations at catchment areas. Additional research points to similar concerns [16], [17]. Population size and geographic location play an important role in the ethical implications of WBE. In 2016, ethical guidelines were developed by researchers in Europe which applied the ethics outlined in the Belmont Report to WBE [10]. The authors of the report propose that ethical guidelines should be interdisciplinary, include ethics committees, and that researchers should take steps to mitigate injury to subjects by using anonymization, communication, and education.

WBE researchers argue that population data does not pose a risk because there is no re-identification of human subjects. Prichard *et al*. [18] assert that WBE does not involve collecting information on individuals, while Hart and Halden [3] claim that privacy is preserved because it is impossible to identify any individual from samples. This anonymity is a consequence of the population size being sampled. However, two recent advances suggest that it is time to revisit these issues. First, it is now feasible to track biological information in wastewater in near real-time. The SARS-CoV-2 studies show that within large samples, we can identify and understand the viral spread and disease trends throughout the population. Second, recent technological advances include widely available, high-capacity computing resources, machine learning and artificial intelligence, as well as improved analytical chemistry techniques. These advances have accelerated what we can feasibly learn from wastewater. A recent study by Pipek *et al*. [6] shows the possibility of identifying human mitochondrial DNA (mtDNA) in urban sewage samples and using that data to estimate the distribution of human mtDNA haplogroups. The presence of identifiable human DNA in sewage mixtures raises new possibilities for wastewater surveillance and genetic analysis. Thus, a careful review is needed of the ethical and policy guidelines facing human genetics data, and it is imperative that WBE adopt best practices from genetic data privacy to wastewater data.

III. PRIVACY AND GENETIC DATA

There is propinquity between the privacy issues facing genetic data and concerns now emerging with sewage data. Understanding this relationship can provide a better context for approaching our current ethical and privacy challenges in WBE. Over the last decade, much genetic data has been moved to open-access databases that promote sharing. Between 2014 and 2019, the National Institutes of Health (NIH) updated policies to encourage open access to genomic data, including Genome-Wide Association Studies (GWAS), single-nucleotide

polymorphism (SNP) microarrays, genome sequence, epigenomic, and gene expression data, obtained through NIH funding [19].

Ethics and data privacy researchers have been vocal about risks of openly sharing genomic data. Even when current best practices are adopted, mistakes and data leaks occur. For example, the Personal Genome Project (PGP), an open repository for volunteers to share publicly genomic and health information, accidentally disclosed the full name of participants by using first and last name as the default naming convention for the database files [20]. Other genomic data attacks have showed that seemingly harmless metadata, such as geographic location, can lead to the disclosure of personal identity. In another exploit, with only birth-date and zip code, it was shown that almost 30% of PGP participants could be reidentified [20]. Since genetic data is unique to individuals and can reveal information about genealogy and health, it is not surprising that researchers have been able to demonstrate many different forms of attack.

Wang *et al.* [21] used a Bayesian network on GWAS to discover a dependency between SNPs and traits. In two attacks using the Bayesian network and meta-data, an individual's private information was identified. Many of the identifiers used in genetic databases are not protected by the Health Insurance Portability and Accountability Act (HIPAA), and there are no policy regulations limiting or protecting their use. Gymrek *et al.* [22] found that adding external metadata to the short tandem repeats on the Y chromosome leads to a 12% chance of recovering a surname. According to Gymrek, this implies that the release of only a few markers can show deep genealogical ties and lead to the identification of a person who may not have consented to the release of his or her information. One of the most famous attacks on identification is by Homer *et al.* [23], who showed how to identify the presence of genomic DNA of an individual of interest in a mixture of DNA samples by using an allele frequency based distance metric. The metric determines whether the alleles of the target individual are closer to those of sample mixture versus a reference population. This result implies that it is possible to show that an individual is statistically likely to be in one mixture compared to another mixture.

These attacks on genetic datasets highlight the many privacy issues surrounding genetic data, but there are other. Genetic patterns in African genomes and other native groups make it easy to distinguish small communities from one another based on genetic samples. This is problematic because it facilitates the reidentification of genetic summary data of an African community [24]. Some North American Native American communities have asked for a tribal review board to provide oversite of any research involving tribal data because of these risks.

When the data involve native and indigenous populations, there is additional ambiguity about ownership. Garrison *et al.* [25] observe that North American tribes are sovereign but often federally funded, creating confusion about what level of consent is required to collect, study, and share their data. Their survey found that tribes identify three groups that should be responsible for the management of data: tribes, universities, and the federal government. Studies where tribal ownership and consent are improperly obtained can cause harm to and exploitation of vulnerable populations [26]. Currently, decisions about to handle genetic data and institute privacy standards are made by groups that do not include vulnerable populations, thus excluding critical perspectives [24]. Without considering the relevant voices in the conversation, proper ethical action is unlikely.

IV. How Researchers Manage Genetic Privacy Issues

For the reasons outlined above, researchers, companies, and practitioners are seeking ways to create robust privacy in genomic data. Anonymization and Beacons are two popular approaches. Anonymization alters data irreversibly in such a way that human subjects cannot be identified [27]. Data anonymization is used in many settings to strengthen privacy in open-access datasets. However, as the research of Homer *et al.*, Gymrek *et al.*, and Wang *et al.* shows, these forms of anonymity may not be strong enough to prevent exploits. Another method for improving security is the use of genomic data-sharing query assessable search engines, or beacons. Genomic data-sharing beacons provide a secure solution for genomic level-data sharing [27]. The Global Alliance for Genomics and Health (GA4GH) provides anonymous access through the web using beacons for genomic researchers to query allele presence [20]. However, this technology is immature and can be vulnerable to exploitation, e.g., by using repeated queries to generate information about a single genome [24].

V. Relationship Between WBE Privacy Issues and Genetic Data

As a new field WBE has an opportunity to draw on existing research in genetic data protection to merge new privacy-oriented practices. Recent research in wastewater has transformed WBE from its traditional epidemiology paradigm to broader considerations of human genetics and traits. With this new information emerging from local catchment areas researchers need more effective methods for sharing samples and data. Because human genetic samples come with ethical and privacy issues, wastewater research may benefit from the example of pioneers in ethical WBE, like Lancaster and Prichard, who expose risks and propose solutions. Incorporating a multidisciplinary approach that includes progress in genetic data privacy will allow researchers to be proactive and to approach the problem systematically. As Shi and Wu say [20], "[T]echnological advances are followed and accompanied by concerns, debates, and controversies on a wide range of topics in ethics, regulations, and laws regarding protection and preservation of genetic privacy. Although in many cases these regulations and laws have lagged behind, they do have significant impact on research, education, and clinical practice of personal genomics." We have an opportunity to be proactive in the field of wastewater analysis and find inspiration, for example, in previous genomics literature to create a roadmap of transition.

VI. In Lieu of a Framework

This section compiles recommendations from the fields of genetic data privacy and wastewater ethics with the aim of initiating discussion among scientists, researchers, and practitioners. Currently there is no framework that considers

how WBE, with the inclusion of genetic data, should progress. In lieu of an existing framework this paper looks at best practices in WBE and genetic data privacy to provide an initial framework. Early action in ethics, interdisciplinary collaboration, organization responsibility, ownership, access control, differential privacy, beacons, query limits, cryptography, and blockchain can each contribute to mitigating risks.

A. Ethics:

Population sample size is often cited as the lynchpin of WBE privacy. Human research ethics committees decline review of WBE studies, labeling them as exempt and non-human research because the population scale analysis is assumed to be low risk [11]. However, there is still a need to consider ethics. For example, Hall *et al.* [11] analyzed how the principles of respect for autonomy, non-maleficence, beneficence, and distributive justice inform our understanding WBE risks. These ideas should be revisited in the context of emerging wastewater applications. Ethical considerations should be periodically revisited together with ongoing review of the sensitivity recovered genetic information. Similarly, the minimum population size threshold, below which a given data point becomes identifiable, is variable, depends on the uniqueness of the analysis target, and should be reviewed regularly.

1) Respect for autonomy: Respect for autonomy builds from the principle of respect for persons in the Belmont Report. The Belmont report outlines the ethical considerations required for human subjects research [28]. Researchers must acknowledge an individual's autonomy and protect those with diminished autonomy. Respect for autonomy can be achieved through consent and full disclosure. In typical WBE research, the population scope means that autonomy is respected. However, if we consider human genetic data, this earlier understanding of autonomy may be called into question. To preserve autonomy, WBE studies that use human genetic information may require human studies review boards. Our earlier understanding of what constitutes 'low risk' may no longer apply, and ethics review boards can validate processes in light of evolving research standards. Population-level analysis complicates the process of obtaining consent. Consent is foundational to respect for autonomy; alternative methods, such as public engagement and communication, may continue to respect autonomy. Those with diminished autonomy or at-risk should be included early in discussions, especially when the research can directly affect policy decisions. Understanding the needs of different groups will enable mechanisms to respect data privacy.

2) Non-maleficence: Research should not harm its subjects. WBE research typically does not cause harm but it could under certain cicrumstances. There are certain groups or locations where wastewater collection could lead to stigmatization or economic loss, such as populations in prisons, environmental venues, schools, or the workplace [11]. Careful consideration and ethics reviews are also needed for research conducted in more isolated locations. If we consider WBE research that extends previous epidemiology into human genetics (even for epidemiological applications), there is increased concern about possible stigmatization, and therefore researchers should carefully discuss and consider the harms and risks. When accessible, mitigation measures such as privacy technologies should be implemented.

3) Beneficence: Another ethical principle fundamental to the Belmont Report is beneficence. Researchers need to ensure that their inquiries maximize benefits and minimize harm. WBE is a growing field with clear benefits for human health through the monitoring of drugs, pesticides, and emerging outbreaks of disease. Using genetic data can also provide a myriad of health benefits. Genetic data is key to understanding human disease and traits. However, researchers need to ensure that the research undertaken continues to provide benefits and reduces harm.

4) Distributive Justice: Fairness is vital to the research process and should not favor one group over another. For example, investigations should not single out a particular economic class or ethnic group. There is evidence that some wastewater collection sites contain more samples of individuals from a given socioeconomic status compared to other collection sites. If there is reason to believe that the distribution of socioeconomic status in a collection site could skew a study, ethical review boards can validate the ethical justice concerns. However, recent WBE studies show that information obtained on socioeconomic status varies based upon external conditions such as weather and is not easy to target [16]. Since WBE studies do not target specific groups and consider population-scale data, justice is preserved in most cases [11], but as the field expands, care must be taken to incorporate distributive justice into the research.

5) Organizational responsibility and data ownership: We know that WBE data can represent populations that are potentially as vast as a megacity, with over 10 million people. Ownership of information gleaned from such samples is unclear. We have some precedent that informs how organizations should handle the concept of ownership in these cases. In 2013 the U.S. Supreme Court ruled that naturally occuring DNA segments are not patentable [29]. However, this leaves tremendous gaps in how researchers, policy makers, public health professional, and corporations working with wastewater should understand ownership. For example, should the ownership question apply strictly to genetic information in wastewater or should it cover the entire handeling of waste? Consent is how ownership of an individual's genetic data is typically approached. However, there is no method to easily gather consent from a large population, especially for use of something typically viewed as innocuous as wastewater. It is impractical to expect researchers to gain consent from every individual in a mega-city. Since there is no clear understanding of how the concept of consent and ownership is changing, public dialog is critical for developing norms and policy. Public engagement can create trust and uphold ethical principles [30]. Citizen engagement is critical for providing open communication on the process. Engaging citizens can help

provide new research questions and ensure that ethical considerations are met. Furthermore, education and ethics training are critical for researchers. Offering researchers ethics training can create greater awareness which then can translate to a community better informed about the benefits and risks of using WBE.

6) Interdisiplinary Approach: By examining ethics, it is clear that respect for autonomy, non-maleficence, beneficence, justice, and communication remains vital. To better engage the community, ensure ethical practices, and provide the best solutions to real-world problems, it is essential to continue to make wastewater-based analysis interdisciplinary. Collaboration across disciplines can accelerate progress while considering the complexities of social interactions and the sciences [9]. Since WBE analysis is engrained within the infrastructure of a city, the social and city dynamics will play a role in ongoing research.

B. Privacy Technology

Relevant privacy enhancing technology can support researchers working with personally identifiable information (PII). The science community is moving toward open data policies to increase research dissemination and reproducibility. Working with data that may contain an individual's personal genetic information means that steps beyond simple deanonymization should be taken to provide appropriate privacy and ethical protections. Genomic privacy tools can provide ethical options in lieu of a current framework and policies.

1) Beacons: A promising technology to facilitate data sharing within the research community are beacons. Beacons allow users to query a data set, e.g., over the Internet, rather than having access to the entire database. Beacons offer more control over queries than more traditioanl user interface systems. Although basic beacon implementations can be exploited [27], [32], [33], some of these problems are mitigated by controlling queriy size and with appropriate access control policies. For example, if users are required to authenticate, the system can limit user query size and frequency; this provides a more robust infrastructure. To alleviate risk to vulnerable communities such as small African tribes, Tiffin [24] proposed that the African Genome Variation Database be available to registered users, with access granted by a review committee and with enfrocement of robust access controls. This would provide an additional level of security for such senstive information.

2) Access control: Access control refers to the policies and methods that are used to control who is allowed what level of access to systems and data. In certain situations, a data access committee may decide who is granted access sensitive data, ensuring a formal process and review.

3) Differential privacy: Differential privacy is a property of some algorithms that anonymize data in a way that guarantees a particular kind of privacy. It can be applied to population-wide sewage sample studies. At a high level, a collection of data is differentially private if the inclusion or exclusion of a single individual from the data set cannot be used to infer much (in a statistical sense) about the individual [20]. Differentially private systems can preserve privacy in the face of random attacks while allowing researchers access to relevant data.

4) Cryptography and blockchain: When personal genetic data is shared, other computational methods available to wastewater genetic researchers. Multiparty computation allows parties with some private data to execute computations together without revealing their inputs or disclosing them to a third party [20]. This is one of the more widely used applications of cryptography in data sharing. Cryptography can allow the necessary analysis of various data while securely sharing WBE information. An alternative to cryptography is a distributed electronic ledger for hosting health information, called blockchain [27]. Using blockchain does not solve the identification problem, but could incentivize data sharing and provide accountability. This would be an option to store personally identifiable information that is used in studies.

VII. FUTURE WORK

When using identifiable data retrieved from WBE studies, researchers can walk through ethical concerns and privacy-enhancing technologies to respond to the complexities emerging in this research field. Genetic literature suggests that, as WBE expands to examining human genetic information, security measures are important for maintaining privacy. Since WBE applications are increasing, more policy and ethics research is needed to ensure rights are preserved. This framework serves as a template to initiate conversations. However, there is an opportunity for future work in this area to examine more detailed solutions to emerging problems and to provide concrete policies for mitigating risks. This paper addresses new possibilities in WBE but preforming risk assessments, such as risks around non-maleficence, is still an open area for research. There is an opportunity to explore the ways to observe and determine risks and provide prescriptive solutions. Members of the team are examining the extent to which genetic material may be identified within WBE samples and what this means in the context of society and data privacy.

VIII. CONCLUSION

Institutions and organizations have an opportunity to start early on the ethical and privacy issues facing wastewater-based analysis. Organizations, such as the NIH, Institutional Ethics Review Boards, policymakers, and the international medical community, can begin meaningful discussions and outline appropriate actions. Discussions must be interdisciplinary and inclusive, so all parties are represented. It is essential to consider social science perspectives and be cognizant of how particular research efforts are likely to affect different populations. When applicable, mitigating measures can be taken to help maintain ethics, data privacy, and citizen security. Whereas the current use of WBE assumes that information cannot be linked back to individuals, this assumption may not hold true in all possible scenarios and as genetic sequence analysis becomes faster, more affordable, and more sophisticated. This paper identifies initial elements of a framework to guide needed discussions. Through early

conversations, we can be proactive rather than reactive in developing policy to accompany the exciting trajectory of WBE. It is vital for those contributing to this field to reflect on the social and ethical issues as the technology advances.

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