

Wastewater and environmental surveillance - a global landscape analysis



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Wastewater and environmental surveillance – a global landscape analysis

The World Health Organization (WHO) has undertaken a qualitative, expert-informed landscape analysis to document the various use cases, technical approaches, governance models and operational realities of wastewater and environmental surveillance (WES) in different country contexts. The findings confirm strong global interest in WES as a complement to other types of public health surveillance, while also highlighting significant challenges related to governance, data use, ethics and its long-term sustainability. This analysis underscores that WES delivers value when it is aligned with national priorities, integrated into decision-making, and supported by clear institutional leadership and sustainable financing. This report calls for country-led approaches, a stronger focus on data interpretation and ethical safeguards, and realistic assessments of costs and capacities to ensure that WES evolves as a reliable and trusted public health tool.

20 June 2025

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Acknowledgments

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Abbreviations

AMR	antimicrobial resistance
CDC	Centers for Disease Control and Prevention (USA)
DHIS2	District Health Information System 2
ECDC	European Centre for Disease Prevention and Control
GIS	geographical information system
GPEI	Global Polio Eradication Initiative
HIC	high-income country
LMICs	low- and middle-income countries
NGO	nongovernmental organization
ODK	Open Data Kit (open-source software)
ODM	Operational Data Model (framework)
PCR	polymerase chain reaction
POLIS	Polio Information System (WHO)
REDCap	Research Electronic Data Capture (digital tool)
SARS-CoV-2	severe acute respiratory syndrome coronavirus 2
SOPs	standard operating procedures
SORMAS	Surveillance Outbreak Response Management and Analysis System
WebIFA	Web Information for Action (WHO)
WES	wastewater and environmental surveillance
WHO	World Health Organization

Glossary

Assay

Sets of validated laboratory tests used to detect specific pathogens or indicators in wastewater samples

Catchment area

The geographical zone from which wastewater flows into a given sampling site; it influences population representativeness and pathogen signals.

Composite sampling

A method that combines multiple wastewater samples collected over a period (e.g. hours or days) to capture average pathogen concentrations and reduce variability

Data normalization

Refers to adjusting wastewater data to account for dilution, the catchment population or environmental factors, thus improving comparability and interpretation

Decentralized sampling

Refers to collecting wastewater from systems such as open drains or manholes, or collecting institutional effluents, which is often necessary where no centralized sewer system exists

District Health Information System 2 (DHIS2):

An open-source health management data platform used globally for collecting, managing and visualizing health data

Digital data platforms

Platforms used for recording, managing and visualizing data; these vary by resource availability and programme maturity.

Early detection (warning)	Identifying signals of potential threats in circulation before clinical confirmation; supports anticipatory public health responses
Environmental sites	Specific locations designated for the collection of environmental samples, especially for surveillance of pathogens in wastewater
Metadata	Contextual information collected during sampling (e.g. time, location, weather conditions, protocol deviations) that improves data quality and its interpretation
Flow-weighted autosampler	An automated device that collects wastewater proportionally to the flow rate over time, commonly used in high-income countries
Grab sample	A single sample of wastewater collected at a specific time and location, representing the conditions only at that moment; often used in low-resource or logistically constrained settings
Geographical information system (GIS)	A system designed to capture, store, manipulate, analyse, manage and present spatial or geographical data
Hybrid systems (sampling):	The combined use of multiple sampling methods (e.g. grab, composite, passive) to adapt to site-specific conditions and objectives

Humanitarian settings	Contexts of crisis, displacement or limited infrastructure where wastewater and environmental surveillance (WES) is proposed but underutilized due to feasibility and ethical constraints
Institutional effluent	Wastewater discharged from specific institutions (e.g. hospitals, prisons, schools)
Multiplex testing platform	Laboratory systems that allow for the simultaneous detection of multiple pathogens or indicators from a single sample
Open Data Kit (ODK)	An open source suite of tools for mobile data collection, used extensively in field epidemiology and environmental health (https://getodk.org)
Passive sampling	A low-cost technique in which absorbent materials are placed in wastewater streams for a defined period of time to capture pathogens, if present; useful in low-flow or hard-to-access areas
Signal variability	Fluctuations in pathogen levels in wastewater due to environmental, biological or operational factors that complicate the interpretation of trends
Points of entry	Locations such as airports, ports or borders that are used to detect threats from imported pathogens
Quality control systems	Standardized procedures and documentation practices to ensure the accuracy, reproducibility and reliability of laboratory data

Research Electronic Data Capture (REDCap):	A secure, web-based platform for building and managing online surveys and databases; commonly used in research and to collect public health data (Vanderbilt University, Nashville, TN, USA)
Sewage	Household wastewater and wastewater-carried solids that flow through sewers to a treatment plant; often used interchangeably with “wastewater,” although the latter is more comprehensive
Standard operating procedures (SOPs)	Detailed, standardized instructions guiding laboratory and field processes to ensure quality and consistency
Surveillance Outbreak Response Management and Analysis System (SORMAS)	An open-source digital platform designed for real-time disease surveillance and coordination of outbreak responses (https://sormas.org/sormas/overview/)
Targeted countermeasures	Public health actions (e.g. testing, vaccination) guided by data from WES and focused on specific sites or populations
Trend monitoring	Ongoing tracking of pathogen levels in wastewater to observe transmission dynamics and assess the impact of an intervention
Wastewater and environmental surveillance (WES)	WES is a passive, community-level public health surveillance tool that consists of the ethical and systematic collection and analysis of wastewater and environmental samples. WES is used to assess the presence or quantity of biological or nonbiological targets and translate those data into a format that supports decision-making. WES complements existing surveillance systems to gain information about various aspects of public health and to improve the decision-making process.

Wastewater and environmental samples

A wastewater and environmental sample is untreated sewage, faecal sludge or other human-impacted water collected from sewers or the environment, such as drains, rivers or ponds. Samples are taken from defined locations where human waste enters water systems. They are collected using different sampling techniques and frequencies and in defined geographical locations to ensure representativeness. These samples are processed to support wastewater surveillance and detect targets circulating in the population.

Web Information For Action (WebIFA)

A digital platform developed by the World Health Organization's African Region that integrates surveillance and laboratory data for public health action (<https://novel-t.ch/projectdetail/webifa/>)

Executive summary

There is a growing need for strategic coordination, documentation of effective practices and clear guidance about how wastewater and environmental surveillance (WES) can meaningfully contribute to broader public health surveillance objectives. Recognizing this need, the World Health Organization (WHO) Health Emergencies Programme conducted a global qualitative landscape analysis of WES implementation.

This report presents findings from 58 in-depth interviews with more than 100 stakeholders from 38 countries, conducted between November 2024 and February 2025. The participants represented a diverse array of institutions and contexts, with the analysis capturing perspectives from those affiliated with national public health agencies, academic institutions, implementing organizations and international bodies.

The primary objective was to improve the evidence base for and to develop a nuanced understanding of WES applications in diverse geographical and operational contexts. These findings will inform WHO's strategic priorities and help identify areas for technical support and the development of guidance.

This research highlighted the complexity of implementing WES, especially in contexts marked by resource constraints, variability in infrastructure and limited institutional integration. WES systems are often shaped by local realities, requiring flexibility in their design and implementation while also demanding harmonized standards to ensure comparability and the wider utility of evidence from WES across settings.

Participants were asked to provide feedback about four main topics, with the aim of improving the application and assessment of WES programmes:

- i. Technical and operational harmonization, including sampling protocols and laboratory methods;
- ii. Data integration and interpretation, focusing on improved linkages to clinical surveillance and risk assessment frameworks;

- iii. Workforce development and institutional capacity-building necessary to sustain long-term implementation;
- iv. Governance and coordination mechanisms to support multisectoral collaboration and strategic alignment.

This analysis confirms that WES is increasingly recognized as a valuable complement to public health surveillance, particularly for capturing population-level signals where clinical surveillance is limited. However, it also underscores that scaling up and sustaining WES depend on resolving persistent challenges related to governance, funding, interpreting the data and ensuring ethical implementation. Without stronger institutional frameworks and clear decision-making pathways, WES risks remaining a project-driven tool with underutilized data and limited public health impact.

This report offers targeted recommendations to WHO, national governments, the global public health community, and WES implementers and researchers. These focus on supporting country-led models, strengthening governance structures and embedding WES into public health systems in ways that are sustainable, ethical and aligned with national priorities.

Key recommendations include:

- i. For WHO – develop an internal strategy to clarify its role in WES, balancing its normative mandate with the evolving maturity of WES, and to support ethical frameworks, technical guidance, and capacity-building without prematurely promoting standardization beyond what the evidence supports;
- ii. For national governments – provide policy support and dedicated financing; leverage existing systems to avoid duplication; and designate lead institutions to strengthen coordination and ownership;
- iii. For the global public health community – align financing mechanisms with country-led priorities; invest in decentralized capacity-

building; and support harmonized but flexible technical standards;

- iv. For implementers and researchers – ensure that WES responds to real public health priorities; engage stakeholders early; build trust; focus on operational relevance; and link research to immediate surveillance challenges rather than purely technical innovation.

This report provides a foundational evidence base to support WHO's continued engagement in WES. It offers practical recommendations and stakeholder-driven insights to guide the strategic embedding of WES into global public health surveillance systems, ensuring that WES evolves as a trusted, ethical and actionable tool that serves national and global public health priorities.



Sewage was sampled from hospitals, penitentiaries and government offices during the COVID-19 pandemic lockdown period, Mexico, 2020. © Julián Carrillo-Reyes

1. Introduction

Disease surveillance systems are adapting to an increasingly complex global health landscape. Traditionally centred on clinical case reporting and laboratory confirmation (1), surveillance has expanded to include alternative data sources constituting a “mosaic of surveillance systems” that offer earlier, broader and more population-level insights into disease dynamics (2). One of the most notable developments in this shift is the growing use of wastewater and environmental surveillance (WES) (3). Although previously applied in specific contexts – such as for poliovirus detection (4) or monitoring the use of illicit drugs (5) – WES gained widespread attention during the COVID-19 pandemic (6). Multiple countries reported implementing WES systems to track severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (7–9).

This recent wave of implementation is largely due to its perceived ability to provide anonymized data that are not biased by clinical care behaviour and laboratory testing capacity, making it particularly relevant for monitoring infectious diseases and public health threats across diverse settings. As countries explore how to transition from ad hoc or emergency deployment of WES towards more routine and integrated WES systems, questions around its governance, sustainability, digitalization and standardization are becoming more prominent (10).

The World Health Organization (WHO) has supported various WES-related initiatives. These include environmental surveillance for poliovirus as part of the Global Polio Eradication Initiative (GPEI) (11), wastewater monitoring for SARS-CoV-2 (12), contributing to tracking antimicrobial resistance (AMR) through the Global Antimicrobial Resistance and Use Surveillance System (13), surveillance for mpox (14) and guidance issued through the water, sanitation and hygiene (or WASH) programme (15).

Despite growing interest in and practical examples of WES, implementation remains variable across countries, and integration into national surveillance systems is still limited. There is a growing need for strategic coordination, documentation of effective

practices and guidance about how WES can contribute meaningfully to broader public health surveillance objectives.

As WES becomes a more prominent feature of disease surveillance efforts globally, it is important for WHO to understand how WES is currently being implemented and its results interpreted and acted on across different WHO regions.

In this context, WHO has undertaken a qualitative, expert-informed landscape analysis to document the various use cases, technical approaches, governance models and operational realities of WES in different country contexts. By listening to the perspectives of public health authorities, technical experts and implementing partners, WHO seeks to gather the evidence necessary to prioritize its actions and provide tailored support to countries seeking to strengthen their WES systems.

This report provides a foundation for WHO to define its role as a technical partner, convener and enabler of effective WES implementation and digital transformation.

1.1 Aim and objectives

The aim of this landscape analysis is to map current WES practices across WHO Member

States and synthesize key insights about the scope of implementation, methods, best practices, challenges and enabling factors. The findings will support stakeholders in making informed decisions and guide efforts to strengthen and scale up WES within national public health surveillance systems.

1.1.1 Objectives

The objectives of this analysis are to:

- Describe how WES is implemented in participating countries, including how sites are selected, and sampling, data collection, transport, laboratory testing, analysis and reporting are performed;

- Identify key stakeholders, enablers, challenges, best practices and lessons relevant to system set-up, sustainability and scale up;
- Assess whether and how WES is integrated into national public health surveillance systems;
- Explore how WES data are combined with data from other surveillance streams for public health decision-making, and identify related opportunities, challenges and effective practices;
- Document existing WES workflows and gather end-user input to inform the design of possible digital WES systems based on open source tools and standards.

1.2 Target audience

The report will help strengthen the understanding of the landscape of current WES practices for the following key stakeholders:

- WHO senior leadership and management;
- departments within WHO involved in WES;
- WHO regional and country offices;
- partners and donors interacting with WHO;
- Member States;
- WES implementers, including those in academia and at research institutes.



Collecting poliovirus samples in Niger, 2024. © Issifi Abdoukader Issifi Kollo

2. Methodology

2.1 Study design

From October 2024 to May 2025, WHO conducted a qualitative study to assess the global landscape of WES use. The study population was those who are implementing WES, collectively termed stakeholders. These stakeholders included subject matter experts in research and academia, and lead personnel at national public health institutes, government ministries and agencies, and regional and global health organizations from all six WHO regions.

Interviews were conducted with individual stakeholders and implementation teams to collect data about a range of topics, including current practices, challenges, best practices, the roles of stakeholders and the future of WES in public health practice. Deductive coding and thematic analyses were performed to synthesize the findings. The output was this report describing the current global landscape of WES and offering targeted recommendations for the future of WES. The complete methodology is available in Annex 1.



Md. Reyaj Patwary collects a grab sample in one of the 53 wastewater surveillance sites in Dhaka, Bangladesh, 2020. © Mami Taniuchi

3. Findings

This chapter details the insights gathered from the qualitative, expert-informed analysis of the implementation of WES across various country contexts. It synthesizes information about different aspects of WES, ranging from site selection and sampling methods to data analysis, decision-making processes and stakeholder involvement, providing a global overview of current practices, challenges and evolving expectations in the field.

3.1 WES implementation: from site selection to decision-making

3.1.1 Site selection and geographical coverage

Across contexts, implementing teams stressed that site selection is informed by multiple, often interrelated, criteria. These include population density, catchment area characteristics, representativeness of the contributing population, accessibility of the site to field teams, proximity to laboratories, flow regularity and the condition of local wastewater infrastructure. Centralized wastewater treatment plants typically include samples from broad populations, while upstream or decentralized sampling points – such as manholes, surface drains or sources of institutional effluents – provide more localized data in settings that may include schools, health care facilities or informal settlements.

“ Site selection evolved over time. Initially, it was based on infrastructure readiness. Now, it’s more risk-based: where outbreaks are likely or where populations are vulnerable. – National public health officer, Western Pacific Region, high-income country ”

Despite these recurring considerations, stakeholders described site selection as a complex and adaptive process. Surveillance needs evolved over time, requiring the addition, relocation or removal of sites based on changing epidemiological priorities, funding availability or the performance of the sites. Often, the utility of a site could not be determined from early data alone, and decisions to retain or discontinue sampling were made only after extended monitoring. Generally, there was difficulty in determining whether a site was “good” or “bad” based on early results. This uncertainty contributed to initial implementation often beginning as a small-scale pilot project, usually located in a capital city, near laboratories or within accessible urban areas. These early efforts prioritized feasibility and proof of concept over national representativeness, leveraging existing infrastructure, stakeholders and logistics. Expansion pathways varied. Some programmes expanded into administrative units; others expanded in response to public health needs, funding opportunities or external partnerships. Many stakeholders described expansions as opportunistic, reactive, filling surveillance gaps during outbreaks or responding to emerging threats.

The lack of rapid assessment tools to evaluate site performance also delayed decision-making about the viability of sampling sites. One participant remarked on the slow feedback cycle:

“ It’s a lot of resources to get to that decision point.... There needs to be a way to more rapidly say, ‘Is this a good place to sample, or not?’” – National public health officer, South-East Asia Region, low- or middle-income country ”

In LMICs, site selection was frequently described as pragmatic and resource driven. Programmes often began by leveraging existing environmental surveillance systems, particularly those developed

for poliovirus, that had established workflows and known access points. This approach allowed for faster scale up, but often meant that sites were chosen based on feasibility rather than representativeness. Commonly cited key drivers of site placement included factors such as transport logistics, the availability of staff and proximity to central laboratories. In some cases, sites were selected because they were already being used or because they were known to be physically accessible, rather than after systematic assessment of their epidemiological value.

“ Selecting the right catchment area is a major challenge...especially in urban slums where infrastructure is lacking or informal.” - Academic/researcher, South-East Asia Region, low- or middle-income country

Adaptations in LMICs often occurred in response to operational issues, such as difficulties in sample collection or laboratory bottlenecks, rather than after proactive performance evaluations. Decisions to retain or discontinue using sites were sometimes influenced by external funding conditions or pilot project timelines, rather than long-term surveillance strategies. In many settings, the capacity to conduct formal evaluations of site performance – such as by assessing the stability of pathogen detection or the representativeness of catchment populations – was limited. However, at the same time, some stakeholders described flexible and adaptive approaches, with sites periodically reassessed based on emerging trends in diseases or changing community dynamics. These adjustments, while sometimes reactive, allowed for a degree of responsiveness in environments where formal evaluation mechanisms were scarce. The expansion of surveillance typically followed a phased and resource-sensitive approach, closely tied to donor cycles or specific outbreaks. Urban centres received attention initially, due to their existing infrastructure, while rural or underserved areas were included only in exceptional, often temporary, initiatives. Many stakeholders described achieving national coverage as an ongoing, largely aspirational, goal.

“ We have a structured method now....Sites are selected in consultation with municipal health services and based on population representativeness.” – National public health officer, European Region, high-income country

In HICs, the approach to site selection was described as structured and systematic. Some programmes used risk mapping, modelling tools or population-based assessments to identify optimal sites by considering geographical equity, coverage overlap with clinical surveillance zones or the anticipated circulation of pathogens. These tools allowed programmes to plan sampling networks proactively and adjust them over time, based on surveillance outputs and public health needs. HICs also reported more frequent and regular re-evaluation of site placement. This included periodic reviews of detection rates, sampling feasibility and spatial coverage. It was common in HICs to use standard operating procedures (SOPs) and internal review processes to determine when to add new sites, adjust sampling frequency or retire underperforming locations. Stakeholders from HICs described more systematic and nationally coordinated approaches, with programmes embedded within public health surveillance frameworks that aimed to achieve equitable geographical representation. Administrative divisions were often used to guide coverage, complemented by mapping tools, demographic analyses and integration with clinical surveillance networks. Stable funding and institutional support allowed for sustained coverage and enabled programmes to adapt their geographical reach based on surveillance outputs, emerging risks or public health priorities.

Yet even in these high-income contexts, those implementing the projects acknowledged enduring gaps. Informal settlements, refugee camps, remote rural communities and areas outside centralized sewage systems remained difficult to incorporate into surveillance frameworks. Some stakeholders shared examples of targeted surveillance efforts designed to reach these populations, often operating independently of broader national networks and

requiring adaptations of the workflow and resource mix.

Despite these differences, there were shared practices across both contexts. Urban areas were almost universally prioritized during early implementation phases due to their infrastructure, population density and logistical convenience. However, while programmes in HICs emphasized ongoing optimization and strategic expansion of coverage, programmes in LMICs described more adaptive and incremental changes, often shaped by practical realities rather than epidemiological modelling.

Further, stakeholders across settings recognized common challenges, such as the persistent difficulty of covering informal settlements, rural communities and areas without sewer infrastructure. These blind spots limit geographical representation. To mitigate this, some stakeholders adopted innovative or supplemental approaches, such as implementing temporary sampling campaigns or targeted monitoring of high-risk zones to fill critical gaps in surveillance coverage.

Rather than framing these coverage patterns as static achievements, stakeholders across settings described them as evolving landscapes marked by negotiation, compromise and adaptation. Many acknowledged that the future of geographical coverage would likely depend not only on technological or logistical improvements but also on the ability of surveillance systems to respond to shifting disease landscapes, funding fluctuations, and the political and social dynamics of public health prioritization. For several, the enduring challenge was how to move from reactive, project-based expansions to more sustainable, equitable models of coverage that could easily adapt to local needs while supporting national and global surveillance goals.

3.1.2 Target pathogens

The range of pathogens and indicators targeted is wide and constantly evolving. It reflected both the historical foundations of environmental surveillance and shifting public health priorities.

Following expansion driven by the COVID-19 pandemic, wastewater surveillance became more

widely used worldwide, and technological advances enabled several programmes to extend their scope to include other respiratory pathogens, particularly influenza virus and respiratory syncytial virus. These additions were seen as logical next steps. However, they also introduced challenges, including the need to validate new assays, update workflows and enhance staff training.

“ We started with SARS-CoV-2 testing during the COVID-19 pandemic, initially out of curiosity, and then expanded to measure [other] virus levels for epidemiological insights.”

– National public health officer,
African Region, low- or middle-income country

Interest also grew in tracking enteric pathogens, including norovirus, hepatitis A and E, and *Salmonella*. Stakeholders described growing interest in these areas, reflecting the adaptability of WES technologies and the desire to leverage existing platforms to achieve broader One Health surveillance objectives.

The uptake of these targets was uneven. While the technical capacity for multiplex testing existed in certain laboratories, stakeholders acknowledged that widespread roll out of multi-pathogen surveillance required sustained funding, standardized protocols and closer coordination with clinical surveillance systems to ensure data interpretability and actionability.

Several participants also referenced the inclusion of non-infectious targets, such as pharmaceutical residues, markers of drug resistance, and environmental contaminants, particularly within academic or pilot-driven initiatives. Although interest in these indicators was growing, stakeholders stressed that such expansions had yet to become part of routine practice in most programmes, remaining largely within the research domain.

Across all settings, stakeholders tried to balance ambition and practicality. On one hand, stakeholders were eager to capitalize on existing platforms to

monitor multiple threats, enhancing the public health value of the system. On the other hand, several cautioned that expanding too rapidly risked overwhelming laboratory capacity, confusing the interpretation of data or stretching the purpose of WES beyond its actionable scope. One participant explicitly illustrated the systemic implications of expanding targets:

“ Adding a new target means more than just another test: it changes how the whole system functions.” – Academic/researcher, African Region, low- or middle-income country

Stakeholders also described the different considerations that affected how they selected and prioritized target pathogens. In some countries, decisions were directed by national health ministries, aligning with public health priorities and surveillance mandates. In others, academic institutions or donor-driven projects led to the introduction of new targets based on research interests or funding opportunities. In both scenarios, the absence of formal frameworks or evaluation criteria meant that decisions about what to monitor were sometimes ad hoc or politically influenced, rather than grounded in systematic assessments of needs or evidence-based processes.

Following selection and prioritization, the expansion of targets was driven by multiple factors, including technical advances, public health innovation and costs. From a technical standpoint, the molecular methods used in most platforms allowed for relatively straightforward adaptation to new targets through the addition of primers or assays. From a public health perspective, stakeholders described an eagerness to leverage surveillance for other priority diseases, particularly as attention shifted beyond the COVID-19 pandemic. Efficiency and cost effectiveness also featured prominently in discussions, with multiplexing and shared workflows seen as strategies to broaden the pathogens covered without incurring proportionate increases in costs or labour.

In LMICs, poliovirus remains the anchor pathogen,

with SARS-CoV-2 gradually added where resources allowed. Further expansion into surveillance for enteric pathogens or markers of AMR was typically donor-driven and limited to time-bound pilots. A few programmes in LMICs had incorporated broader targets, for example by piloting the inclusion of *Mycobacterium tuberculosis* or other pathogens, but very few of these projects evolved into sustainable national strategies.

“ So far, all surveillance is primarily for poliovirus. Then we started small pilot studies for other pathogens.” – National public health officer, African Region, low- or middle-income country

In contrast, stakeholders from HICs described a broader and more rapidly implemented expansion of target pathogens. Beyond SARS-CoV-2, programmes in these contexts often included suites of viral and bacterial pathogens, such as norovirus, rotavirus, adenovirus, influenza, and markers of AMR. These additions were enabled by broader technical capacity, access to multiplex or high-throughput testing platforms, and closer collaboration with established surveillance systems. Target selection was typically informed by ongoing public health concerns and used to monitor seasonal trends, emerging pathogens or AMR risks. These programmes also had established mechanisms for reviewing and adjusting target lists over time, ensuring alignment with evolving surveillance needs and laboratory capabilities.

“ We included all the known viruses [and] all the non-viruses that are known to cause acute risk.” – National public health officer, Eastern Mediterranean Region, high-income country “

3.1.3 Sampling methods

Globally, two primary approaches were used for sampling: grab sampling and composite sampling. In grab sampling, implementing teams collected a single sample at a specific point in time. This technique was widely used due to its low cost and ease of deployment. This method was particularly popular in low-income settings or during the early phases of programme implementation, when logistical and technical barriers limited the feasibility of more complex methods.

“ In many cities, grab samples are all we can do due to equipment limitations and [problems with] site access.” – Academic/researcher, Region of the Americas, low- or middle-income country

Composite sampling involved collecting samples over an extended period, typically several hours in a day or a full day. This method accounted for fluctuations in wastewater flow and improved the representativeness of the sample. Many stakeholders described composite sampling as the preferred approach due to its ability to smooth temporal variability and provide more consistent data about trends. In HICs, teams routinely used composite sampling as the standard approach. They relied on flow-weighted autosamplers. Implementing teams in LMICs were hesitant about adopting an autosampler, citing unreliable access to equipment and technical support, and concerns about devices being stolen.

“ We have standardized procedures now: 24-hour composite samples, analysed two to three times per week.” – National public health officer, European Region, low- or middle-income country

In some settings, implementing teams used autosamplers for composite sample collection.

One drawback was that autosamplers are vulnerable to theft, especially in areas lacking secure or enclosed infrastructure. These concerns often led programmes to rely on manual grab sampling as a practical, albeit less scientifically rigorous, alternative. Nevertheless, teams adopted creative workarounds for enhancing sample representativeness in the absence of autosamplers.

These included:

- Timing grabs during peak flows;
- Pooling multiple grabs; and
- Tailoring workflows to local wastewater management practices.

These efforts reflected a commitment to ensuring data quality, even in constrained environments.

Sampling frequency typically ranged from once to twice per week. However, sampling intervals were frequently adjusted based on surveillance objectives, resource availability or emerging public health needs. During periods of high transmission or outbreak alerts, some programmes increased the frequency of sampling to provide more timely data for decision-making. Stakeholders emphasized the flexibility required in scheduling, with several describing the need to align sampling times with peak wastewater flow hours to optimize sample quality, particularly when using grab sampling methods.

Teams adapted their methods to accommodate decentralized sewer networks. In these areas, they collected samples from open drains, manholes or points where institutional effluent was discharged. Where possible, they introduced standard protocols, trained field staff regularly and used written SOPs to ensure consistency across sites.

During the COVID-19 pandemic, many teams began using passive sampling by placing absorbent materials in wastewater flows for extended periods. This method offered a low-cost alternative in areas where active sampling was difficult or unsafe, particularly in those with intermittent flow or minimal infrastructure. While passive sampling showed promise, teams continued to refine protocols and improve interpretation frameworks to validate its effectiveness.

Many programmes, particularly those operating at scale or across diverse environments, developed multiple sampling workflows to account for variations in site conditions, infrastructure and surveillance targets. Stakeholders described hybrid systems in which grab sampling was used at certain sites, while composite or passive methods were used elsewhere, depending on feasibility and objectives. This pragmatic, site-specific approach was widely recognized as essential for ensuring the sustainability and effectiveness of WES programmes in diverse operational contexts.

Across income settings, stakeholders consistently acknowledged trade-offs between methodological ideals and practical realities, recognizing that the choice of sampling method was not straightforward. They noted that while technical guidance often favoured composite sampling, field conditions required ongoing compromises. Moreover, as WES systems evolved to include new pathogens or expanded their geographical coverage, stakeholders described grappling with the question of whether their sampling methods remained fit for purpose. For many, these decisions were not fixed but part of an ongoing process of negotiation, shaped by evolving disease priorities, funding dynamics, and the operational experiences of field and laboratory teams. Thus, sampling methods were not simply technical choices, but holistic considerations of the wider systems in which WES operated.

3.1.4 Data collection

Field teams paired sampling methods with standard data collection procedures that ensured the traceability, reliability and comparability of results. These data collection procedures, as described across contexts, involved both technical protocols – such as labelling schemes, data entry tools and digital tracking systems – as well as broader institutional practices to address data quality. There were variations in these approaches across countries and programmes that often reflected broader differences in infrastructure, resource availability and system maturity.

The data collection process typically began at the sampling site, where field teams recorded metadata, including collection time and date, location identifiers, information about environmental

conditions and textual documentation of any irregularities in the sampling process. They collected data using standardized forms or templates, either paper-based or digital, depending on the technological capacity of the programme. In low-income settings, the Open Data Kit (ODK) open-source digital system (Get ODK, <https://getodk.org>) was popular; it has forms for site specification, sample collection and a basic checklist. Implementing teams in HICs used proprietary systems such as REDCap (Research Electronic Data Capture, Vanderbilt University, Nashville, TN, USA) or in-house systems such as EpiSurv (<https://epi-surv.phfscience.nz/help/>), developed by the New Zealand Institute for Public Health and Forensic Science. In many programmes, ensuring strong coordination between field teams and laboratory personnel was seen as vital for maintaining data accuracy and integrity. Labelling practices, including the use of barcodes or alphanumeric identifiers, were considered critical data quality measures for ensuring linkage between the physical sample and its metadata throughout the chain of custody.

Stakeholders also described workflows in which data collection was integrated into broader operational routines. In several programmes, metadata were recorded during sample collection, with systems designed to capture information in real time or as part of standardized field protocols. Where infrastructure permitted, these practices were supported by digital tools, such as Power BI (Microsoft, Redmond, WA, USA), the ODM (Operational Data Model) framework (Clinical Data Interchange Standards Consortium, Austin, TX, USA) or STARLIMS (Hollywood, FL, USA), that allowed for more efficient data entry and reduced the risk of transcription errors. However, stakeholders also acknowledged that such systems required investment in equipment, connectivity, training and maintenance, which could present barriers in certain contexts, particularly in low-income settings.

Another recurring theme was the role of central laboratories or public health institutes in managing and archiving data once they were collected. Stakeholders described how field teams would transfer samples to centralized facilities, which also served as data repositories. In some cases, these facilities maintained digital dashboards or centralized surveillance platforms, while in others,

data storage relied on spreadsheets or offline records, reflecting disparities in technological capacity and system maturity.

Stakeholders in low-income settings described more fragmented or semimanual data collection practices. Initial data capture was often done using field notebooks or spreadsheets, with data later transcribed into local databases or maintained as paper records at national laboratories. Mobile-based systems were mentioned in some instances as tools to bridge infrastructure gaps, but these were rarely standardized or consistently applied across programmes. Stakeholders acknowledged that while these workarounds met immediate needs, they also posed the risks of data loss, transcription errors or delays in reporting, especially when operating across wide geographical areas with limited connectivity.

Stakeholders from more established or better-resourced programmes often described highly structured and digitized data collection systems, featuring barcoding, automated data entry, and centralized platforms linking sample identifiers with their collection location, date and laboratory results. These systems were frequently integrated into broader surveillance databases and supported by institutionalized quality assurance mechanisms. In these settings, data collection was portrayed as routine and embedded, benefiting from secure infrastructure and reliable connectivity.

“ We are open to adopting digital systems if they are user-friendly and can integrate with existing platforms.”

– National public health officer, South-East Asia Region, low- or middle-income country

Across settings, stakeholders shared a common belief in the importance of data integrity and traceability to the credibility of surveillance outputs. Regardless of whether systems were highly digitized or largely manual, stakeholders articulated a clear commitment to maintaining rigorous data management practices and recognized the need to ensure reliable linkages between samples and their associated metadata. This commitment was reflected in efforts to develop SOPs, provide regular

training and implement systems for chain-of-custody tracking, even in challenging environments.

Stakeholders also discussed the future evolution of their data collection systems. While some, particularly those in more mature programmes, described satisfaction with their current systems and expressed little interest in change, others saw data collection as an area ripe for improvement, innovation and investment. Several stakeholders from low-income settings expressed interest in piloting digital data capture tools, integrating mobile applications or enhancing interoperability with laboratory systems. However, they also acknowledged that to ensure sustainability, such ambitions would require external support, capacity-building and careful planning.

Rather than positioning data collection practices in public health surveillance as settled or universally progressing toward digitalization, stakeholders portrayed them as deeply dependent on the context, shaped by the interplay of infrastructure realities, workforce capacity and institutional priorities. Many observed that data collection practices will need to evolve as surveillance systems expand to include new pathogens, cover wider geographical areas or integrate with other public health data streams. For some, the challenge lay in scaling up or formalizing systems that had grown organically during emergency responses. For others, it was about safeguarding the simplicity and reliability of existing methods while exploring new efficiencies. These perspectives illustrated the common understanding that data collection is not merely an operational step, but an ongoing negotiation among ambition, feasibility and the evolving demands placed on surveillance systems.

3.1.5 Laboratory methods and standardization

Laboratory methods emerged as a central pillar of WES. Molecular techniques, particularly polymerase chain reaction (PCR), featured prominently across programmes. PCR-based approaches were widely used for detecting pathogens such as poliovirus, SARS-CoV-2, and other viral and bacterial targets. Many WES programmes used PCR, but some included reverse transcription-PCR for enhanced analysis. Beyond PCR-based detection, sequencing

technologies were described as playing a growing role in several programmes. These used sequencing to characterize SARS-CoV-2 variants or to conduct broader genomic analyses of wastewater samples.

“ Our work in the laboratory starts with the extraction of the nucleic acids from the samples, which are then screened with [reverse transcription]–PCR. If positive, we send [the samples] for sequencing.”

– National public health officer, European Region, low- or middle-income country

Such applications were generally associated with programmes that had advanced laboratory infrastructure or engaged in specialized partnerships, often as part of pilot initiatives or supplementary research activities. A smaller subset of programmes used metagenomic methods to capture a wide range of organisms without targeted assays. However, stakeholders were quick to caution that these approaches were resource-intensive and largely confined to exploratory settings rather than routine surveillance.

A few stakeholders described culture-based methods used primarily for pathogens when the recovery of viable organisms was necessary, such as for poliovirus. These methods were integrated within historical surveillance frameworks and were occasionally combined with molecular confirmatory testing.

There were considerable variations in laboratory capacity; the standardization of methods, processes and workflows; and infrastructure. Many WES programmes conducted testing within national laboratories, while others relied on centralized facilities for sample processing, particularly in systems with limited decentralized laboratory infrastructure. Although few stakeholders outsourced testing to foreign laboratories, the reliance on centralized laboratories in some countries suggested that resources were concentrated in a few key institutions, with implications for sample transport times, data turnaround and system flexibility.

Quality control measures and the use of SOPs were widely reported as essential practices for ensuring consistency and data integrity. Stakeholders described using internal controls, replicates and inhibition assays, and the incorporation of multiplex assays, where feasible, to improve efficiency. However, in many programmes, testing for each pathogen was still conducted separately, reflecting resource limitations or the absence of standardized methods and validated multiplex assays for certain targets.

In low-income settings stakeholders described a constrained palette of laboratory methods, in which PCR or reverse transcription–PCR represented the core diagnostic approach. Many of these methods were inherited from poliovirus surveillance systems and were extended to newer targets, such as SARS-CoV-2, during the COVID-19 pandemic. While some programmes in LMICs reported using sequencing technologies, these were typically limited to pilot initiatives or conducted in collaboration with external partners or centralized reference laboratories. Stakeholders in these settings described common challenges related to the availability of equipment, reagents and skilled personnel, and to the maintenance of laboratory infrastructure. Centralized laboratories often served as the hub for processing samples from multiple regions, reflecting a necessary efficiency but also introducing challenges related to transport logistics and data turnaround times.

Stakeholders described a dilemma between the aspiration to adopt cutting-edge laboratory methods and the practical realities of sustaining reliable, scalable workflows. Even though the COVID-19 pandemic accelerated interest in advanced technologies – such as next-generation sequencing, digital PCR and multiplex platforms – several stakeholders acknowledged that their systems would likely not have the capacity to sustain the use of these technologies in the long term, particularly once emergency funding diminished. Many programmes made a trade-off by prioritizing methods that were well established, affordable and compatible with existing workflows, even if that meant sacrificing some degree of scope, sensitivity and specificity of detection.

In high-income settings, stakeholders reported

routinely using a wide range of molecular and genomic techniques. PCR and reverse transcription-PCR remained the backbone of detection, often supplemented by multiplex assays enabling simultaneous detection of multiple pathogens. Sequencing technologies, including next-generation sequencing and metagenomic approaches, were frequently used to monitor variants or conduct broader surveillance. These methods were supported by well-equipped, centralized laboratories with robust quality control systems, automation and digital workflows that contributed to timely sample processing, data analysis and reporting.

In summary, the global landscape of laboratory methods reflected institutional dynamics and important developments in recent years. Some stakeholders emphasized that established protocols were adequate for their surveillance goals, especially where resources or infrastructure limited the feasibility of more advanced approaches. Others pointed to clear gaps and highlighted aspirations to adopt more sensitive, standardized, multiplexed or genomic approaches, but noted that such advances would be possible only with sustained investments in training, validation processes and data interpretation capacity.

3.1.6 Data analysis and reporting

Stakeholders described data analysis and reporting as integral components of WES systems, shaping how raw laboratory data were transformed into actionable information for public health decision-making. Analysis was framed as a multi-layered process involving not only validating and processing laboratory results but also interpreting, contextualizing and communicating findings. Stakeholders emphasized that this phase required interdisciplinary collaboration, involving laboratory scientists, data analysts, epidemiologists and public health officials, to bridge the gap between technical data outputs and meaningful public health insights.

Across contexts, stakeholders described a range of analytical approaches, from basic positive-negative reporting (i.e. presence or absence) to more complex analyses that incorporated data normalization, integration with clinical data streams and trend modelling. In some programmes, particularly those monitoring poliovirus, the primary analytical goal

remained the detection of any positive signal.

“ So if we have any signal from the wastewater, then we initiate field investigations and, if needed, clinical sampling as well.”

– National public health officer, Eastern Mediterranean Region, low- or middle-income country

For monitoring SARS-CoV-2 and other pathogens, however, the emphasis shifted towards quantifying the pathogen load, examining spatiotemporal trends and integrating auxiliary data sources, such as clinical case counts or demographic information. Stakeholders noted that in these cases, WES was positioned as part of a broader epidemiological mosaic, complementing clinical surveillance and providing an additional lens into community-level disease dynamics.

A recurring theme was the challenge of managing signal variability, described by some data analysts as the “noise” in wastewater data (Box 1). They identified numerous factors contributing to the complexity of this challenge, such as:

- Pathogen biology;
- Assay sensitivity;
- Sampling methods;
- Environmental conditions, for example rainfall and temperature patterns;
- Population dynamics within the catchment area; and
- Physicochemical characteristics of the wastewater matrix.

These variables were described as highly interdependent, with variability in one area often amplifying uncertainties in another. Stakeholders acknowledged that these challenges made interpreting wastewater data inherently context-dependent, requiring in-depth, site-specific knowledge, and stakeholders cautioned against overinterpreting trends or attempting to estimate precise infection counts from wastewater signals. As one participant remarked, such attempts might:

“Go beyond what the surveillance system [WES] can provide.”

– Public health expert, African Region, low- or middle-income country.

Data normalization practices in the context of WES emerged as a methodological grey area and source of inconsistency. Some programmes adjusted pathogen concentrations using markers such as pepper mild mottle virus (known as PMMoV), estimations of catchment area populations and flow rates. However, stakeholders noted that approaches are not standardized across programmes, underscoring the ongoing challenges of ensuring comparability between sites and over time.

Stakeholders described a variety of formats for disseminating reports, including informal exchanges, formal reports, interactive dashboards and peer-reviewed publications. The choice of reporting channels was often influenced by the target audience, urgency of findings and institutional relationships. Stakeholders underscored the importance of tailoring outputs to the needs of public health officials and policy-makers, and using visual clarity and simplicity, such as easily understandable figures, to ensure that results were accessible and actionable. Several stakeholders described the use of smoothed averages and data visualization tools to minimize noise and highlight underlying trends, particularly when communicating results to non-technical audiences. As one participant explained:

“On the dashboard, it had to be very visual and very simple...just breaking [data] down using some smooth averages over time to take away the noise because wastewater surveillance is quite noisy.”

– Health informatics expert from government public health institution, Region of the Americas, high-income country

Reporting was often described as an iterative process, with formats and content adjusted based on stakeholder feedback and evolving information needs.

In low-income settings, stakeholders described similar analytical goals but more constrained infrastructure. Data analysis was often conducted manually or using basic spreadsheet tools, and visualizations were typically developed by academic or technical partners. There were challenges related to data consistency, including variability in sampling and transport timelines, which affected the quality and timeliness of reporting. Reporting formats were generally limited to PDFs, internal summaries or shared data sheets. Some programmes experimented with public dashboards, although these remained less sophisticated and less accessible than in high-income settings. Stakeholders frequently noted that additional support was needed to strengthen the translation of laboratory data into actionable public health insights, particularly where technical and epidemiological capacities were limited.

“Electronic data systems are needed for real-time communication. We use Excel and meetings due to funding constraints.”

– Academic/researcher, Eastern Mediterranean Region, low- or middle-income country

Stakeholders from high-income settings described sophisticated analytical systems supported by dedicated data science teams, integrated data infrastructure and automated pipelines. These systems enabled rapid processing of laboratory results into visual summaries, dashboards and time-series analyses, used to detect trends, compare sites and flag deviations from expected patterns. Several programmes reported integrating wastewater data with clinical, syndromic or hospital admission data, and some incorporated auxiliary data to contextualize findings, such as weather patterns or population mobility data. The reporting cycle in these settings was often regular and timely, with weekly bulletins or real-time dashboards ensuring that stakeholders received up-to-date information to inform public health actions, especially during public health emergencies.

Stakeholders across all contexts recognized the expanding expectations placed on WES outputs,

particularly following the visibility gained during the COVID-19 pandemic. While many programmes aspired to provide more timely and accessible evidence from integrated data, stakeholders acknowledged persistent challenges in building sustainable analytical capacity, institutionalizing reporting workflows, and ensuring that surveillance outputs were trusted and used by public health decision-makers. Some stakeholders emphasized the risks of overloading fragile systems with analytical

expectations that exceeded their core capacities. They cautioned against moving too quickly towards predictive modelling or highly granular interpretations without first consolidating basic analytical and reporting processes.



Box 1. The importance of contextualizing results from wastewater surveillance, Mozambique

In Mozambique, wastewater surveillance teams have learned that environmental and human factors must be carefully considered when interpreting results. A sample that appears to show a low pathogen concentration may not necessarily indicate a decline in disease circulation. Without fully understanding the geographical and social contexts in which wastewater samples are collected, the interpretation of data can be misleading.

One factor that affects wastewater sampling is rainfall. During the rainy season, wastewater samples often show reduced pathogen concentrations, not because infections have decreased, but because heavy rains dilute the contents of the sewage system. This is particularly evident in certain regions where flooding regularly disrupts sample collection and analysis. Surveillance teams must consider seasonal variations and adapt their collection schedules accordingly.

“We ask the collection team not to sample on rainy days because we know the samples will be too diluted.” – Maurice Neyitegeka, environmentalist and epidemiologist, Ministry of the Environment

Urban infrastructure also plays a role in shaping wastewater data. If a sampling site is close to a business that discharges significant volumes of water, such as a car wash, then that can alter samples.

Human behaviour further complicates wastewater surveillance. In certain areas, waste disposal patterns fluctuate throughout the day, leading to inconsistencies in the composition of samples. This means that the time of day when samples are collected can influence the results, requiring teams to adjust sampling strategies to capture more representative data.

“Sometimes the time of collection or variation [in the] behaviour of people or ... season can dilute samples. For example, sometimes people don’t get up early. Thus, we need to do the critical thinking to see why our results are not good. Why our results are not as expected”. – Maurice Neyitegeka, environmentalist and epidemiologist, Ministry of the Environment

Another key consideration is site selection. For example, in areas where centralized sewage systems are lacking, such as informal settlements, open defecation may be common, meaning that not all human waste enters the monitored wastewater system. This requires surveillance teams to acknowledge that wastewater data alone may not fully represent disease circulation in these settings, and alternative approaches may be needed.

3.1.7 Decision-making using evidence from WES

Stakeholders described decision-making in the context of WES as a complex, multistep and often evolving process, closely tied to how data were interpreted, communicated and embedded within broader public health systems. While WES data offered a valuable new lens into community health, stakeholders consistently emphasized that its influence on concrete decision-making remained highly variable and was shaped by:

- The maturity of public health systems;
- The credibility of the data;
- Institutional relationships, especially between research and public health agencies; and
- The broader context of governance.

Nevertheless, there were many tangible examples across different contexts in which wastewater data contributed to decision-making in triggering targeted public health action, for example in:

- Initiating diagnostic testing in areas showing high viral signals;
- Strengthening public health messaging;
- Reallocating health resources, such as personnel and materials; and
- Deploying vaccination campaigns.

Recurring examples included the use of wastewater data to monitor variants of SARS-CoV-2 and for mpox surveillance.

Further, many researchers described more indirect ways in which wastewater data were used. They acknowledged that the evidence they generated contributed more often to general situational awareness, background monitoring or evidence-based discussions with public health authorities, without necessarily leading to immediate and direct interventions. Sometimes, researchers were not aware whether the data they generated from WES was even used for decision-making.

There was a consensus among all interviewees that WES was rarely positioned as a standalone decision-making tool. Instead, findings were interpreted alongside other data streams, including those from

clinical testing, syndromic surveillance, clinical data or sentinel reporting. Using data from WES along with other data was viewed as essential for validating wastewater signals, assessing their significance in relation to other indicators and determining appropriate responses. Researchers described this multisource approach as particularly important in settings with high uncertainty or where wastewater data were perceived as noisy or subject to multiple confounding variables.

As part of discussions between researchers and public health authorities, there were joint efforts to develop formal decision-making pathways. Some programmes had developed structured frameworks that included predefined thresholds or triggers linked to wastewater signals. This was especially the case during the COVID-19 pandemic, when rapid decision-making was required. These frameworks provided clarity and enabled faster action. In many settings, however, stakeholders described more informal, iterative and relationship-based decision-making processes, often occurring without formalized protocols or clear criteria for action. Decisions were shaped through dialogue, negotiation and consensus-building among stakeholders, and decisions sometimes relied heavily on the judgment of individual actors or the influence of key decision-makers.

In stakeholder deliberations about how to position wastewater surveillance within decision-making processes, institutional embedding of WES programmes emerged as a key prerequisite. In high-income settings, stakeholders described WES as being integrated within broader surveillance and health information systems, with the resulting data feeding into routine public health coordination mechanisms, dashboards and situational reports. In these contexts, wastewater data were routinely reviewed, trusted and acted upon (Box 2).

There were examples of use cases in which wastewater supported decisions, such as implementing localized interventions in schools, congregate settings and neighbourhoods, and tailoring the public health messaging of risk communication teams. In low-income settings, stakeholders described a more emergent or transitional role for wastewater data in decision-making. While there were examples of wastewater

data triggering targeted public health actions, such as intensified clinical testing, these were less common.

More often, wastewater data served as a supportive tool, contributing to awareness but not directly driving interventions. Those implementing WES described challenges including a limited capacity for interpreting data, policy-makers who were unfamiliar with environmental surveillance, and delays in sample processing and reporting that undermined the timeliness and usefulness of data. Some stakeholders noted that decision-making pathways for wastewater data were underdeveloped and relied on ad hoc presentations to authorities or discussions within small technical groups, rather than being embedded in institutionalized planning frameworks.

“We created a dashboard, for instance. But... [policy-makers] have not used the information for actions about decisions.”

– Academic/researcher, Region of the Americas, low- or middle-income country

In settings where environmental surveillance had a longer history, such as in poliovirus programmes, researchers reported that public health authorities were more ready to consider data from WES about other pathogens and incorporate it into decision-making. Conversely, where WES was newer, stakeholders observed that more effort was required to build awareness, communicate the value of the data and align outputs with the expectations of decision-makers. Communication strategies – including the use of dashboards, smoothed averages and simple reports – were considered essential tools for making wastewater data more understandable and actionable for non-technical audiences.

Stakeholders noted that there were frequently trade-offs between scientific uncertainty and decision-making imperatives. They observed that it was challenging to use wastewater data as a basis for important decisions, owing to its inherent variability, lack of specificity and the difficulty in quantifying infection prevalence. Some reported that decision-makers were sceptical of the data, particularly when

wastewater signals appeared to conflict with clinical data or when interpretation required complex contextualization. Others described the importance of framing wastewater data appropriately, using it to inform trends and guide further investigations rather than as definitive evidence for action.

Political considerations also shaped decision-making processes. In both high- and low-income settings, decisions around the use of wastewater data were sometimes influenced by political sensitivities, reputational concerns or the public perception of risks. Some participants described decision-makers being reluctant to act on wastewater signals without corroborating evidence from clinical surveillance, fearing there had been misinterpretation or would be backlash. Others shared examples of decision-makers being more receptive to wastewater data during emergencies, only to de-prioritize it once the immediate crisis waned.



Box 2. Wastewater and environmental surveillance in Singapore: an adaptive, data-driven approach to public health monitoring

Singapore operates a wastewater surveillance programme designed for agile adjustment to shifting epidemiological needs. Supported by a network of more than 500 sampling points, the system is not fixed to a single purpose but continually reoriented so that it can have the greatest operational impact.

During the COVID-19 pandemic, wastewater data were deployed in a targeted way: pinpointing specific residential apartment blocks that showed increased viral signals, which triggered on-the-ground swab testing and quarantine measures. As case-based needs changed, the scale of sampling could be reduced or sampling could be redeployed to other points without dismantling the overall system. Today, even with reduced clinical testing, wastewater continues to be used to monitor trends and detect emerging variants, ensuring that early signals remain available even without maintaining the full-scale pandemic footprint.

This capacity to scale and redirect resources is also applied beyond COVID-19. For mpox, wastewater testing is activated during periods of heightened international transmission to provide situational awareness and inform readiness measures. For Zika virus, wastewater results are layered with clinical case detection and mosquito surveillance, enabling authorities to identify potential hotspots and respond with targeted vector control measures. As public health priorities shift, sampling using the same infrastructure can be paused, intensified or switched across pathogens.

Singapore's National Environment Agency is also continually evaluating operational pilot programmes, such as testing wastewater from incoming aircraft, improving wastewater surveillance systems to detect new pathogens or assessing new sampling tools.

A defining feature of the programme is its emphasis on using wastewater data as a trigger for action rather than for background monitoring. Results from wastewater surveillance are integrated with clinical and epidemiological information, allowing public health authorities to act proportionately by mobilizing resources, directing testing and communicating risks, when and where needed. The system remains deliberately agile, able to shrink, expand or pivot in response to changing disease patterns, without losing its readiness for rapid activation.

Singapore's approach illustrates how wastewater surveillance can function as a modular, responsive component of public health surveillance, anchored in case-based use that is adaptable in scope and able to serve both operational needs and targeted research without locking into static programme structures.

3.1.8 Data-sharing

Data-sharing emerged as a critical yet uncommon practice among WES programmes. Among participating stakeholders, researchers were more familiar with data-sharing and more eager to share data in the fast-evolving field of WES. However, they were measured in their expectations and observed that the ways in which data were shared between partner

stakeholders varied widely across contexts and were informed by differences in:

- Surveillance system maturity;
- Institutional mandates;
- Data governance structures;
- Technological capacity; and
- Political sensitivities.

In two programmes in high-income settings, stakeholders described more established and open data-sharing systems in which they shared data sets freely on their GitHub repositories. They noted how several researchers, including PhD students, leveraged their open data-sharing practice for their work. However, in many settings data access was restricted and either only for internal use or limited to specific institutional partners. Reasons for restricted sharing included concerns about data sensitivity, and uncertainties about interpretation and reputational risks, and the lack of clear data ownership arrangements.

These concerns were particularly acute when data were collected from locations associated with identifiable populations, such as specific communities, institutions or vulnerable groups, where privacy concerns, stigmatization or political sensitivities could arise. In programmes in which surveillance was embedded within national public health systems, the existing provisions of data-sharing processes extended to WES data. These provisions were generally more structured and supported by formal policies, memoranda of understanding or embedded guidelines within national surveillance strategies. Conversely, pilot projects or research-led programmes often relied on more informal data-sharing practices, facilitated through direct communication or personal networks, or implemented in response to specific requests from stakeholders.

For many participants, data-sharing remained one of the most politically and operationally sensitive dimensions of WES implementation, seen as a space where technological solutions had to be matched by attention to trust-building activities, negotiation, and the social and political dynamics that shaped how data flowed, who accessed it and how it was ultimately used for public health action.

3.1.9 Stakeholders involved in implementation

The implementation of WES programmes was a highly collaborative endeavour, involving a range of stakeholders that spanned government ministries, academic institutions, international organizations, donors, entities in the private sector and, occasionally, NGOs. Ministries of health were most

frequently identified as the central coordinating body, especially in LMICs, where they were often responsible for integrating WES into national public health frameworks. In several contexts, ministries of health, with support from international development partners, also held responsibility for designing the system, budgeting and ensuring alignment with national surveillance strategies.

3.1.9.1 National and subnational stakeholders

Many ministries and organizations contributed to a programme's development, delivery and oversight, reflecting the cross-sectoral nature of wastewater systems and the complementarities of the required technical, regulatory and public health competencies. In many settings, other key ministries – such as the ministries of environment, water and infrastructure – were not only involved but were also initiators of WES programmes. These actors contributed through their roles in managing wastewater treatment systems, overseeing water and sanitation infrastructure, regulating environmental health and ensuring access to sampling sites. Their participation was often critical for securing logistical support, facilitating cross-sectoral coordination, and ensuring that surveillance activities aligned with broader environmental monitoring or municipal service delivery systems and mandates. Some programmes had formal interministerial coordination mechanisms, such as governance committees, memoranda of understanding or task forces. However, these arrangements were frequently short term, donor-facilitated or crisis-specific.

At the subnational level, there was broader participation of public institutions in WES that included local health agencies, municipal governments, wastewater utilities and environmental regulators. These subnational actors were often responsible for sample collection, logistics and laboratory processing, as well as ensuring standardization of procedures across multiple sites. In decentralized systems or in areas with fragmented infrastructure, local authorities played critical roles in negotiating access to sites, coordinating sampling schedules and addressing operational barriers in the field.

3.1.9.2 Academia and research institutes

Academic and research institutions were widely described as essential technical partners that played multiple roles, for example in laboratory testing, developing sampling methods, training personnel and, in some cases, leading pilot projects or operational surveillance components. Stakeholders across the board observed that these institutions often served as intermediaries between field implementation and public health authorities, translating technical data into actionable insights and supporting advocacy efforts to promote the added value of WES within national and local health systems. In several cases, particularly in LMICs, academic institutions led early WES efforts, managing laboratories and coordinating field operations in the absence of strong public sector capacity. Universities were key players in scientific innovation, developing sequencing protocols and validating assays, especially for novel targets such as markers of AMR or SARS-CoV-2 variants.

“We are a research group, but we ended up becoming operators. We were operating the wastewater testing for large portions of our region.”

– Academic/researcher, Region of the Americas, high-income country

Yet there were structural limitations: academic engagement was often project-based, depended on external grants and rarely integrated into national systems. As a result, while academics drove technical advances, their roles in governance, policy or funding allocation remained minimal, limiting pathways for a transition from research to a sustainable, integrated surveillance system.

3.1.9.3 International organizations

International organizations were described as key supporters, particularly in countries where WES systems were scaled up rapidly during the COVID-19 pandemic; some of the organizations named were WHO, the United Nations Children’s Fund, the United States Centers for Disease Control and Prevention (CDC), the European Centre for Disease Prevention

and Control (ECDC), the Institut Pasteur, various NGOs and global research consortia. These actors contributed funding, technical assistance, protocols, training resources and support for capacity-building. International research partnerships fostered by these organizations played important roles in expanding testing capabilities, supporting genomic sequencing and facilitating the cross-country exchange of knowledge. The involvement of these organizations was seen as a source of technical legitimacy, shaping national protocols and reporting practices.

“Our [organization’s] role is to provide some of that technical expertise but also to help coordinate some of this across state lines.”

– International organization

However, some national actors expressed concern about the challenges of balancing international input with the need for domestic ownership. They noted that while external actors enabled the rapid expansion of a programme, transitioning towards a sustainable, nationally led system remained a common challenge.

3.1.9.4 Donors and NGOs

Donors played central roles in LMICs, including the Gates Foundation, the Global Fund to Fight AIDS, Tuberculosis and Malaria, the Japan International Cooperation Agency, the US Agency for International Development and the World Bank. They provided funds to establish systems, upgrade laboratories and train staff in surveillance and outbreak response. Stakeholders credited these actors with enabling WES in contexts that had limited capacity. However, a donor’s priorities often influenced the focus of a programme, the timelines and data-reporting obligations. Some stakeholders reflected critically on this influence, noting that short-term, project-based funding created coverage gaps and operational fragmentation when donor cycles ended.

“The funding that I have mostly comes from the Gates Foundation. They’ve been the ones that have supported almost all of our environmental surveillance work from 2015.”

– Academic/researcher, South-East Asia Region, low- or middle-income country

In HICs, donor involvement was nearly absent. National agencies fully financed and operated WES systems, occasionally engaging donors in research consortia but without relying on external funding for core surveillance activities.

NGOs and civil society organizations were involved only sporadically in WES. When their engagement occurred, it was largely in an auxiliary capacity. They focused on community engagement, risk communication or supporting sampling in hard-to-reach areas. Most stakeholders did not view the absence of NGOs as a major gap, citing the technical and institutional nature of WES. However, some acknowledged that NGOs might have potential value in decentralized models in the future, especially in fostering community acceptance and supporting outreach to informal settlements or remote areas.

3.1.9.5 The private sector

Private sector engagement also depended on the context of the programme, and it was often limited to providing services through contractual arrangements. Private laboratories, technology firms and logistics providers supported functions such as laboratory analysis, sample transport and supplying equipment

“[Private company] would be able to put equipment in the 27 labs for nothing...Costless.”

– Academic/researcher, Region of the Americas, low- or middle-income country

In a few cases, private actors led pilot programmes in wastewater treatment or environmental monitoring but these remained peripheral to formal national systems.

“In 2023, finally, together with the health secretariat from the city, we were able to contact the company, the private company, that covers the sewage for most parts of our city, to really start working together. And it was absolutely wonderful.”

– Academic/researcher, Region of the Americas, low- or middle-income country

Stakeholders pointed to tensions around data confidentiality, the sustainability of programmes and programme oversight, emphasizing the need for public control over core surveillance activities. Nonetheless, emerging models of public-private partnerships, particularly in urban or resource-constrained settings, were considered promising avenues for expanding coverage and innovation.

3.1.9.6 Coordination strategies of stakeholders

Coordination mechanisms to manage the involvement of diverse WES actors varied widely. Some countries had structured systems in place, with interagency committees, steering groups or technical platforms that had formal roles and procedures. Others relied more heavily on informal communication, personal networks or ad hoc arrangements, especially during emergencies. Stakeholders emphasized that successful implementation hinged less on the presence of specific institutions and more on the quality of coordination, with successful coordination involving clear roles, sustained communication and alignment across agencies that had divergent mandates and institutional cultures.

In contexts in which multiple ministries or sectors were engaged, stakeholders acknowledged that coordination was complex but necessary. Programmes that included actors from the health, environment and infrastructure sectors appeared to

benefit from shared resources, broader institutional support and stronger cross-sectoral buy-in, particularly in relation to site access, the integration of infrastructure and the long-term sustainability of the programme. Conversely, in settings where coordination was weak or siloed, stakeholders described tensions over data ownership, fragmentation of responsibilities and duplication of efforts.

3.1.10 WHO's contributions and evolving expectations

Stakeholders described WHO as a central actor in shaping the development of WES. Its role has been visible across technical, institutional and political dimensions, while expectations of WHO continue to shift as programmes expand beyond legacy areas. The following sections explore how these contributions have been perceived in practice and the ways in which countries and partners envision WHO's future engagement.

3.1.10.1 Technical guidance

WHO's contribution to WES was most recognized in its leadership in poliovirus surveillance and surveillance for SARS-CoV-2 during the COVID-19 pandemic. Stakeholders regarded technical guidance from WHO as an authoritative reference for WES programmes. WHO's contribution was described as both foundational and catalytic, particularly through its provision of SOPs, protocols and laboratory methods for environmental surveillance for poliovirus. These resources provided a basis for ensuring methodological consistency, laboratory quality and data comparability across countries. Stakeholders described guidance documents from WHO as conferring legitimacy and structure to the programmes. Guidance documents offered a critical starting point for national adaptation, especially in contexts facing tight timelines or responding to emergent threats.

WHO's support was also seen to extend into operational domains, such as site selection and system optimization. WHO's provision of reagents and proficiency testing was credited with ensuring consistency across countries and alignment with international reporting systems. WHO was also commended for its responsiveness in updating

protocols and supporting laboratory adaptations to accommodate varying equipment and field conditions. This flexibility was perceived to be critical for operational efficiency and credibility, especially in contexts where national guidelines were absent or being developed. Furthermore, researchers considered guidance from WHO as key in shaping training curricula, informing national reporting practices and serving as an authoritative tool during early advocacy and planning phases.

“We are working now with the WHO country office and sometimes we have support from the Regional Office for Africa...[for] materials, technical support, digitalization, identification of the site and the monitoring of results.”

– National public health officer, African Region, low- or middle-income country

For more established programmes, WHO's contribution was seen as providing valuable high-level reference material and reassurance during strategic transitions, such as when surveillance was expanding to new pathogens or coverage was being scaled up. Many advanced national programmes had developed their own detailed protocols, methods and dashboards that were grounded in internal expertise and regulatory frameworks. The contribution of WHO in setting up general frameworks, helping with pathogen prioritization and highlighting ethical considerations was seen as useful for developing alignment with technical documents and innovation driven by national or regional institutions.

“WHO has a lot of clout...People are still wondering, ‘Should we do it or not?’ We should only do it if WHO recommends it. A position paper from WHO would be very useful.”

– National public health officer, Western Pacific Region, high-income country

While WHO's guidance was viewed as well established and highly valued for poliovirus surveillance, several participants emphasized that technical frameworks for broader multi-pathogen surveillance – including for monitoring AMR and other emerging targets – remained limited or under development. This gap was seen as creating uncertainty for countries attempting to implement broader surveillance efforts, and it reinforced the need for more detailed, actionable and globally recognized standards that could support harmonized, scalable programmes across different pathogens and contexts.

This gap forced countries to develop or adapt local methods, often relying on academic research or bilateral collaboration, resulting in fragmentation and inconsistency across programmes. Many stakeholders explained that expanded and detailed guidance from WHO would help foster more systematic, harmonized and comparable approaches.

“For other viruses...if there is a standard SOP like what we have for polio, it is very convenient....If WHO [did] this for us, [it would be] very good.”

– Academic/researcher, Eastern Mediterranean Region, low- or middle-income country

In some cases, it was noted that WHO's technical guidance lagged behind operational needs, particularly during rapidly evolving public health situations, necessitating interim local solutions.

3.1.10.2 Capacity-building

WHO's contribution to capacity-building for WES was largely viewed through the lens of its longstanding contributions to poliovirus surveillance. In the early stages of environmental surveillance for poliovirus, WHO provided direct training, and help with laboratory set-up, workforce development, operational oversight and laboratory quality assurance. Its involvement was seen as highly visible and influential, particularly in countries where national capacity was initially limited or non-existent.

“We do not deny the support from the WHO regional office in [country X], which supported us with trainings....They have a fingerprint that we cannot distort.”

– National public health officer, Eastern Mediterranean Region, low- or middle-income country

Many programmes in HICs had little engagement with WHO-led capacity-building activities for WES. Instead, national programmes relied primarily on domestic partnerships between academic and public health institutions to develop technical and institutional capacities. The expectations of WHO in these settings were largely focused on convening global technical discussions and issuing high-level guidance documents, rather than on providing direct support for workforce development or institution strengthening.

Across settings, there was a clear expectation that future capacity-building efforts by WHO should extend beyond legacy disease programmes. Public health officials called for:

- Structured training initiatives focusing on WES;
- Support for laboratory readiness for multi-pathogen testing;
- Enhanced capacity for public health decision-makers to interpret and act upon WES data;
- More proactive contributions to field-based training and mentoring; and
- Facilitation of cross-sector institutional learning.

“WHO could support this effort by providing funding for training programmes, hiring personnel and organizing courses.”

– National public health officer, Region of the Americas, low- or middle-income country

3.1.10.3 Coordination

WHO's contribution to coordination has been most established and visible within the context of poliovirus surveillance. WHO has played a central role in managing laboratory networks and facilitating the regional flow of data. In some countries, WHO was credited with facilitating discussions between ministries, donors and laboratories, thus contributing to the development of national surveillance frameworks that benefited WES. At the global level, WHO's coordination activities were primarily seen through its technical webinars, working groups and forums for dialogue.

While WHO has coordinated global spaces that are valuable for peer exchange and sharing experiences, these were not perceived as sufficient to address the operational coordination challenges countries faced in implementing programmes. Stakeholders observed that these forums lacked follow-up processes, actionable outputs or clear pathways for sustaining coordination beyond the events themselves. The engagement of WHO in broader WES efforts was seen as fragmented, largely reactive and lacking structured mechanisms beyond sporadic technical dialogues.

“I would like to see an overview of who in WHO is working on what, and how the pieces of your puzzle fit together....That could give some confidence to externals in terms of what's happening in that space.”

– Academic/researcher, African Region, low- or middle-income country

Many saw the global position of WHO as offering a unique opportunity to foster alignment and cross-country dialogue. Yet this potential was described as underutilized, particularly in supporting operational alignment and intersectoral coordination at the national level.

One public health official expressed uncertainty about WHO's leadership approach for WES:

This suggests a lack of clear direction from WHO and it implies a desire for a more collaborative and

inclusive process in developing WHO's guidance, rather than a top-down approach.

“People were still wondering, ‘Should we do [WES] or should we not do [WES]? ‘Should WHO convene an expert committee to come up with that position, so that it can be a consensus among some experts and countries?’”

– National public health officer, Western Pacific Region, high-income country

3.1.10.4 Contribution to advocacy

WHO's advocacy was recognized for helping to position WES as a credible public health tool, particularly during the COVID-19 pandemic, when its endorsement increased acceptance among policy-makers and donors. During the pandemic, WHO recognized WES as a complement to clinical systems, and this was instrumental in encouraging its use during pandemic response efforts.

Further, the contribution of WHO as a convener of technical discussions and communities of practice was seen as instrumental in supporting the early strategic framing of WES, particularly in relation to AMR, mpox and pandemic preparedness in general.

Stakeholders observed that WHO's current advocacy fell short in addressing the specific challenges countries face in transitioning from single-pathogen surveillance, such as for poliovirus, to broader multi-pathogen approaches. They noted that advocacy efforts tended to be implicit – embedded within technical guidance or reports – rather than delivered through direct engagement with political leaders, donors or senior decision-makers.

“WHO can also help with high-level advocacy to get us the support that we need to be able to implement [WES].”

– National public health officer, Western Pacific Region, low- or middle-income country

This was viewed as a missed opportunity, particularly in contexts in which visible WHO advocacy could help national stakeholders secure political buy-in, domestic financing or donor investments. Participants called for stronger messaging from WHO to promote WES as an essential component of public health preparedness and surveillance systems, rather than as an optional or experimental tool.

“WHO can influence the policy of [country]....I hope to see that happen for wastewater-based epidemiology.”

– National public health officer, South-East Asia Region, low- or middle-income country

Both researchers and public health officials emphasized that WHO's advocacy could be strengthened by showcasing successful country models and use cases, endorsing pilot projects and promoting demonstration initiatives that illustrate the practical and strategic value of WES. WHO's platforms and global credibility were seen as underutilized assets that could more effectively influence high-level decision-makers, especially in settings where WES remains undervalued or politically contested.

3.2 Use cases: turning wastewater into public health insights

Ministries of health, national public health agencies, researchers and their collaborators consistently agreed that WES was not a replacement for existing surveillance modalities. Instead, they described it as a tool for strengthening the sensitivity of the overall system, as well as its coverage and timeliness. This complementary function was described as particularly valuable during periods of reduced demand for clinical testing, to validate or triangulate syndromic and clinical data, or to provide broader population-level insights. Stakeholders described WES as operating independently of individual health-seeking behaviour and providing continual, passive community-level signals that captured asymptomatic cases and populations disengaged from formal health care services. They considered this feature of WES to be particularly valuable

during the early phases of an outbreak, in contexts of policy-driven reductions in clinical testing or in settings experiencing testing fatigue. They explained that when WES results are interpreted alongside case reports, hospitalization data or syndromic surveillance, wastewater signals can help to confirm observed trends or raise flags when other data sources appear inconclusive. Some described WES as detecting silent transmission or residual viral circulation in communities before clinical confirmation of an outbreak, raising the index of suspicion for clinicians. These suspicions, in turn, could prompt targeted public health follow-up actions, including diagnostic testing, outbreak investigation or intensified communication with local health authorities.

These stakeholders viewed the dynamics between WES and clinical systems as mutually reinforcing, with clinical surveillance providing case-level, pathogen-specific data, and WES offering broader situational awareness and information about trend continuity. This complementarity of WES supported risk communication and the prioritization of resources, and guided public health interventions, particularly when the findings of the systems were interpreted together rather than in isolation. Across LMICs and HICs, stakeholders cautioned that where WES operated in isolation, or without purposeful alignment to routine systems, its value as a complement was diminished, highlighting the need for deliberate design of WES systems and operational alignment to maximize its contribution to public health surveillance. Overall, five complementary areas of WES use emerged, with varying levels of adoption, based on stakeholders' priorities and capacities as detailed in sections 3.2.1–3.2.5.

3.2.1 Early detection (warning) and outbreak preparedness and response

The contribution of WES to early warning of disease outbreaks was consistently recognized as a benefit that WES added to existing clinical surveillance systems. Many participants emphasized that WES provided population-level health signals before clinical cases were detected or confirmed through traditional surveillance systems.

This anticipatory capacity was noted as a

distinguishing feature, particularly during the COVID-19 pandemic: several respondents observed that wastewater signals often preceded clinical case surges by several days or weeks. WES was able to capture viral shedding from asymptomatic and presymptomatic individuals. This allowed surveillance systems to detect changes in community transmission that might otherwise have gone undetected, particularly in settings where diagnostic testing was limited, delayed or affected by care-seeking behaviour.

“WES has the potential [to act as] an early warning system, for Salmonella typhi. At least a few days ahead [of] or during [an] outbreak, we are seeing more higher positivity signals in wastewater....And also the clinical surveillance for typhoid is very resource intensive.”

– National public health officer, South-East Asia Region, low- or middle-income country

Some participants observed that WES filled a critical surveillance blind spot during the early phases of outbreaks or in areas with restricted access to diagnostic services. There was a consistent recognition among participants that the value of surveillance data for outbreak or pandemic preparedness was inseparable from the capacity to act upon it. Participants cautioned that generating data without pathways for response could erode trust, cause frustration among public health actors or create ethical concerns. Many implementing teams raised this concern, observing that,

These observations underscored the need for preparedness systems to ensure not only detection capabilities but also clear response mechanisms and decision-making protocols that allow WES data to be translated into actionable interventions.

“We consider [WES] as a powerful tool for pandemic preparedness and prevention that provides health information at the community level. [It] promotes health equity by the inclusion of underserved groups because it does not address the individual, [but] rather a community, and [it is a] low-cost complement to the clinical surveillance system.”

– National public health officer, South-East Asia Region, low- or middle-income country

3.2.2 Monitoring trends in disease and public health threats

Across contexts, stakeholders described trend monitoring as a widely recognized and relevant benefit of WES to policy-making. They explained that the ability of WES to generate continual, longitudinal data allowed surveillance systems to track patterns of disease transmission over time. This offered insights into the persistence, decline or resurgence of pathogens at the population level. This consistency distinguished WES from clinical surveillance, which can fluctuate due to changes in testing behaviours, health care access or protocols.

“We often saw trends in wastewater before cases appeared in clinical data. That gave us a window to act early.”

– Academic/researcher, Region of the Americas, high-income country

Participants observed that the relatively stable and passive signals WES generates provided a valuable basis for assessing longer-term trends, informing preparedness activities and validating the impact of public health interventions. Many emphasized that WES supported routine monitoring activities, such as weekly reporting, which allowed public health authorities to observe fluctuations and assess the duration of waves of diseases.

Additionally, several participants distinguished between the trend monitoring and early warning

functions of WES. While early warning focused on the acute detection of emerging outbreaks, trend analysis allowed programmes to observe the trajectories of transmission, including rises, declines and plateaus in viral load over time. Implementing teams also noted that WES supported the detection of residual or resurgent signals following major waves of outbreaks, contributing to public health vigilance during periods when there was a low incidence of reported cases. This function was seen as supporting decisions about whether to scale down, maintain or adapt other surveillance activities.

“Knowing the start of the season and knowing the end of the season would be helpful in terms of ensuring efficient use of the resources, and so this is one of the reasons why we were very interested in wastewater surveillance for [respiratory syncytial virus].”

– Academic/researcher, African Region, low- or middle-income country

Researchers and academics explained that generating reliable trend data from WES depended on technical requirements, namely maintaining consistent sampling schedules, and using standardized laboratory workflows and rigorous quality control practices to preserve trend clarity and data comparability. Some described applying data-smoothing techniques or data normalization (e.g. for flow rates, population equivalents, environmental variables) to improve interpretability, especially in decentralized or variable environments (e.g. those affected by drought, floods, freezing temperatures).

Beyond infectious disease surveillance, some programmes have begun to explore using WES to monitor trends in behavioural and chemical markers, such as drug metabolites, antibiotic resistance genes or industrial pollutants. This was described as expanding WES into a broader public health and environmental monitoring platform.

In some HICs, public health personnel described WES trend monitoring as an embedded component

of surveillance architectures. WES trend data were integrated into public dashboards, weekly briefings and institutional risk assessments. WES trends were often disaggregated geographically, allowing health officials to monitor variations across catchment areas in near real time. With access to stronger analytical infrastructures and professional networks, some HICs were able to model trends more precisely and align WES insights with other surveillance systems, such as AMR monitoring frameworks.

Public health authorities recognized the important operational benefit of WES in supporting targeted countermeasures. WES enabled authorities to identify areas of concern, monitor transmission dynamics and inform the deployment of specific interventions, such as testing campaigns, vaccination drives, communication activities or intensified public health measures. WES was seen as providing population-level signals that could help direct resources and attention to specific communities, catchment areas or facilities, thus supporting more strategic and efficient public health responses. Some programmes used WES to target interventions to closed settings, such as schools, correctional facilities or care homes.

“Whenever we detected a signal, we would trigger swab operations in the area.”

– National public health officer, Western Pacific Region, high-income country

Across LMICs and HICs, implementing teams described the potential of WES to inform targeted countermeasures as being widely recognized but operationally variable, and dependent on a system's maturity and integration into broader frameworks for moving from surveillance to response, and on the readiness to make decisions. They explained that without established response protocols and institutional mandates, WES risked remaining a surveillance input rather than a trigger for targeted countermeasures.

3.2.3 Use in recurrent, planned mass gatherings

Most participants from public health authorities explicitly stated that using WES during recurrent, planned mass gatherings was either not part of their surveillance strategy or not discussed by their programme. A few acknowledged the theoretical value of WES in providing discreet, population-level monitoring during high-density events, such as festivals, religious gatherings or sporting tournaments, and suggested that it could support the early detection of pathogen circulation and inform situational awareness.

However, these considerations remained largely conceptual, with no concrete examples of systematic application across settings. When mentioned, stakeholders described using WES in these contexts as exploratory or linked to isolated pilot projects, noting there were significant challenges in logistics, data interpretation and integration into existing public health response frameworks. This finding was consistent in both LMICs and HICs.

3.2.4 Use at points of entry

The use of WES at points of entry, such as airports and border crossings, emerged sporadically during discussions. Stakeholders offered a range of views regarding the possible benefits of WES at points of entry, although the theme remained marginal within the broader discussions of operations. Several participants explicitly stated that points of entry had not been a focus of current or past WES strategies. When the concept was considered, participants cautioned that while these locations might present theoretical opportunities for the early detection of imported pathogens, operational realities remained challenging, such as the feasibility and justification of the surveillance and its integration into existing systems.

“With respect to aircraft, those [considerations] are very problematic. I saw some really clever, intelligent sampling devices [but] I think it’s a risk for the people that sample. I think the information is quite biased, so I think aircraft [sampling is] not a very good idea.”

– National public health officer, European Region, high-income country

Stakeholders recognized that airports and other points of entry might serve as important nodes for detecting new introductions of diseases. However, they questioned whether the implementation of WES in such settings would yield actionable data or fit within existing surveillance mandates. Some described these considerations as being at an exploratory stage, with the concept having been debated but not yet formalized into routine practice or protocols.

3.2.5 Use in refugee camps and humanitarian settings

The use of WES in refugee camps and humanitarian settings was limited and originated from a small subset of research institutes and governmental entities operating in humanitarian and emergency contexts (Box 3). Many programmes indicated that such settings were outside the scope of their current surveillance priorities. They did not consider this limited practice to be a critical gap, but rather that it reflected the targeted nature of their programme.

A few programmes deployed WES in these settings as part of outbreak preparedness activities. These focused on detecting poliovirus, *Vibrio cholerae* and SARS-CoV-2. Teams raised concerns about the feasibility of implementing routine WES during humanitarian responses, citing challenges related to unstable infrastructure, transient populations and the difficulty of sustaining surveillance systems in crisis-affected areas. In one programme, WES data from a refugee camp prompted community-level actions, such as public education about handwashing and food-handling.

Even though implementation teams indicated that data from WES in these settings supported public health planning and responses, such as risk communication, they did not claim definitive outcomes on health impacts. In these deployments, ethical considerations were explicitly raised about the sensitivity of working within refugee camps. Teams emphasized the need for responsible data-handling, clear communication strategies and attention to community dynamics to ensure that surveillance outputs were used in ways that respected local populations and did not inadvertently contribute to stigma or anxiety.

Across both LMICs and HICs, there was a consistent

lack of systematic examples of WES in these settings, indicating that while WES might hold potential for humanitarian settings, its practical use, institutionalization and integration into emergency health frameworks remain underdeveloped.

From this experience, the West Bank and Gaza Strip demonstrate that an integrated, multisectoral approach – in which environmental monitoring is aligned with public health strategies – can serve as a model for sustainable water management. With adaptable and interoperable surveillance platforms, such strategies can be further refined to meet evolving water security challenges while maintaining public health protection.



Box 3. Integrating environmental and wastewater surveillance in the West Bank and Gaza Strip

The West Bank and Gaza Strip face a persistent challenge of water scarcity, necessitating innovative solutions for sustainable water management. One critical approach is the recycling of wastewater, coupled with periodic water quality testing to ensure public health and environmental safety. Despite logistical and operational challenges, complete coordination between the Ministry of Health, the Water Authority, academic institutions and international stakeholders has been instrumental in advancing WES.

In the West Bank and Gaza Strip, a structured approach to wastewater monitoring enables the systematic collection of environmental, epidemiological and laboratory data. This integrated effort ensures that water quality assessments are conducted regularly, providing real-time insights into potential contaminants and risks to public health. By leveraging the expertise of multiple agencies, both national and international, a collaborative network has been established to address key concerns related to water safety, efficiency in recycling processes and the sustainability of water resources.

The environmental surveillance system not only facilitates the identification of potential risks but also strengthens decision-making processes for public health interventions. For example, as soon as traces of cholera are present in the water, health teams are sent out for an investigation. The involvement of universities ensures a scientific foundation for research, while international partnerships provide technical expertise and funding to enhance infrastructure and capacity. A coordinated, well-trained network of professionals contributes to the effectiveness of this system, ensuring that quality-controlled data are used to guide policies and interventions.

“[The West Bank and Gaza Strip are] not only a [territory] under water stress, but also a health critical [territory], along with all districts in [the territory]. To avoid and to protect people from additional contamination, WES has, of course, an added value,... which means that wastewater surveillance now is a must. It’s not a luxury.”

– Mohammad Al Hmaid, CEO Palestinian Water Sector Regulatory Council

3.3 Unpacking the challenges of implementing WES

3.3.1 Technical challenges

Stakeholders encountered a wide range of technical limitations in the practice of WES. These constraints were not confined to specific laboratory processes but extended across all stages of the surveillance cycle, from field sampling to data interpretation. Technical challenges were perceived as deeply embedded in the operational realities of WES, often entangled with institutional, logistical and methodological difficulties. These challenges disrupted not only the scientific aspects of surveillance but also the credibility of the data produced, influencing how stakeholders and public health authorities perceived and acted upon findings from WES.

Stakeholders consistently explained that technical challenges represented a persistent and multifaceted struggle within WES operations. They described how environmental samples demand specialized handling and introduce complexities that standard diagnostic laboratories were often ill-prepared to address.

“The wastewater signal is more noisy than what we get from a clinical test or even hospital admissions.”

– National public health officer, Region of the Americas, high-income country

Several implementing teams experienced the rapid degradation of wastewater samples during transport due to insufficient cold chain capacity or delays. This degradation had direct effects on the reliability of analytical outputs.

Stakeholders in LMICs shared their experiences of the foundational nature of the technical barriers they faced. Many described laboratories that were originally set up for clinical diagnostics or poliovirus surveillance but were then pressed into service for environmental testing, often without the necessary adaptations, so they lacked a dedicated infrastructure for wastewater analysis. As a result,

sample transport, storage and laboratory processing were compromised. Some stakeholders described scenarios in which the absence of local testing capacity forced them to ship samples abroad for analysis. This delayed results, reduced national ownership of the data and strained limited budgets.

Supply chain vulnerabilities were especially prominent in LMIC settings, where stakeholders described persistent difficulties in obtaining essential consumables, such as filters, extraction kits and reagents. These difficulties led to reactive surveillance practices, in which samples were processed only when materials were available, thus disrupting regular surveillance schedules and compromising data continuity. Researchers explained that these disruptions weakened the credibility of evidence from WES.

“Now, we have kits for [only] 3 months. This is the challenge that we have.”

– Academic/researcher, Eastern Mediterranean Region, low- or middle-income country

In contrast, the focus of stakeholders in HICs centred more on optimizing and refining existing technical systems rather than overcoming gaps in basic infrastructure. While acknowledging that environmental samples posed inherent analytical complexities, stakeholders in HICs described well-equipped laboratories with automated processes, trained personnel and relatively stable supply chains.

However, even within these settings, stakeholders faced challenges related to methodological consistency. The need to harmonize protocols across jurisdictions, particularly for emerging pathogens beyond SARS-CoV-2, arose as a pressing concern because the lack of standardization undermined the comparability of results. Across all contexts, there was a shared frustration among stakeholders regarding the absence of harmonized protocols and validated methods for processing wastewater samples. Some described how laboratories were compelled to develop or adapt procedures under tight timelines, especially during the initial phases of surveillance implementation, relying on improvisation rather than established standards.

This lack of methodological consistency introduced variability among laboratories and undermined confidence in trend analyses. As a result, stakeholders faced difficulties in reconciling disparate results across different sites. Technical challenges were more common during pilot phases, when the technical fragility of systems was exposed in practice and adaptations were yet to be made.

“Everybody having a different understanding of what they think is a right way, or a different way, or to do [the analyses], you are not then going to be able to compare apples with apples.”

– Academic/researcher, African Region, low- or middle-income country

Despite these challenges, stakeholders considered their experience to be a learning curve that required continual adjustments and capacity-building, recognizing that technical strengthening was not a single event requiring investment but an ongoing process that demanded institutional commitment, reliable systems for maintenance and expertise to support sustainable WES operations. They cited ongoing efforts within their networks to build resilience by increasing collaboration and capacity. Some described how sharing SOPs and participating in technical training workshops helped to foster more consistent practices. Further, technical hubs and regional collaborations provided support for troubleshooting and harmonization, although stakeholders emphasized that these efforts were limited in scope and often depended on temporary external support.

3.3.2 Financial challenges

Financial constraints were not perceived as transient events but as systemic conditions shaping decisions around how surveillance could be initiated, sustained and expanded. Whether securing funds for initial set-up, maintaining day-to-day operations or integrating surveillance into routine health systems, stakeholders described financial considerations as inseparable from the technical, logistical and institutional aspects of their work.

“The first challenge is funding... especially where clinical data are lacking.”

– International organization

Funding from donors or emergency grants, particularly during the COVID-19 pandemic, allowed many WES programmes to start quickly by providing the means to purchase equipment, hire staff and begin collecting samples. However, such financial arrangements proved fragile. The absence of mechanisms to secure continuity left programmes in an uncertain position once the triggering emergencies were under control. The transition from crisis response financing to stable, domestic support was uncertain and, in most cases, unrealized.

Beyond initial investment, the common challenge was to maintain funding for operational costs. The expenses associated with routine tasks were considered significant, including those for field logistics and cold chain maintenance, laboratory consumables and personnel. Meeting these expenses was more challenging in settings where samples had to be transported long distances or laboratories operated at limited capacity. Some stakeholders noted that as programmes matured or sought to incorporate more advanced techniques, such as sequencing, financial pressures intensified, with new layers of costs requiring sustained investment in reagents, software and workforce training.

“Blocking factors? Always funding: convincing the decision-makers that it’s worth it to invest and to keep investing and to have sustainable funding that is secured for many years. I think that is the main issue.”

– International organization

Stakeholders also observed that it was difficult to secure formal recognition of the importance of WES within domestic health financing systems. Even when ministries or institutions were supportive in principle, it was challenging to convince planners and financial officers to consider WES alongside more established public health interventions. This

perception of WES as novel or supplementary was described as a recurring obstacle to achieving predictable, routine funding, leaving many programmes reliant on external partners and unpredictable, project-based grants.

Administrative inefficiencies further complicated financial management. Several stakeholders cited procurement bottlenecks, delays linked to foreign currency shortages and rigid public procurement policies ill-suited to the specific needs of laboratories or field teams. Even when funding was allocated, these barriers created uncertainties about spending, delayed activities and increased operational costs, particularly in decentralized or newly established programmes.

The fragmentation of financial streams was also a common challenge. Programmes were often supported by a patchwork of donors, institutions and local authorities, each with their own timelines, requirements and strategic objectives. While this allowed surveillance to remain active in some contexts, it placed a burden on coordination, planning and reporting. The lack of a unified financial structure further limited the ability to scale up programmes or advocate effectively for them.

There were also emerging efforts to shift these dynamics, although the stakeholders recognized these were in the early stages or only partial. In some settings, co-financing models were explored to bring together the health, environment and infrastructure sectors to diversify financial support. Other stakeholders shared examples of leveraging preparedness and early warning narratives to secure more sustained attention from both domestic and donor agencies. Some of the pragmatic approaches they adopted to reduce dependency on single sources of funding included initiating partnerships with private sector actors and integrating WES into existing environmental monitoring frameworks. However, stakeholders were cautious in their expectations, acknowledging that while these approaches offered temporary relief or opportunities to expand activities incrementally, they had yet to displace the underlying structural gaps that, in general, left surveillance systems vulnerable to financial volatility and fragmented support.

In LMICs, programmes often depended on short-term donor funding or project grants. This dependency left systems vulnerable to abrupt discontinuation when funding cycles ended, regardless of the technical success or political support achieved. The absence of domestic budget lines or formal financing mechanisms restricted a programme's ability to plan or expand beyond the initial pilot phases. In these contexts, financial instability shaped not only the scale of activities but also the confidence of stakeholders, and interrupted sampling, laboratory processing or staffing. These financial constraints were further compounded by inefficiencies in public financial management systems. The slow pace of procurement processes, restrictions on international purchases and unpredictable exchange rates added layers of complexity, introducing delays, raising costs and making operations increasingly reactive rather than strategic.

In HICs, financial pressures often reflected challenges in prioritization within well-established public health budgets. While surveillance activities in these settings were supported by government funds, scientific grants or institutional budgets, there was the need to continually justify expenditures, particularly during periods of reduced public health urgency. As a result, to align with budgets, several programmes in these settings had to scale back their sampling frequency, narrow the range of pathogens targeted or postpone the adoption of new methods. Even in more robust financial systems, stakeholders observed that WES still had to compete for space and recognition within broader national health strategies, and this required advocacy as well as alignment with existing reporting and decision-making structures.

3.3.3 Infrastructure challenges

Stakeholders considered infrastructure challenges as more than issues of sewage networks and sample collection. They included a range of physical, digital and institutional systems that support the implementation and maintenance of WES. From how urban spaces and wastewater treatment infrastructure were designed to the condition of transport systems, data platforms and laboratory access, stakeholders described infrastructure as a central determinant of whether and how surveillance could be implemented, scaled up or sustained. Gaps in transport infrastructure, including unreliable roads and limited cold chain capacity, were described as frequently affecting sample quality and processing timelines.

Fragmented, incomplete or outdated wastewater systems held back the implementation of surveillance. Several stakeholders observed that while surveillance was most straightforward in areas with modern, centralized sanitation networks, such conditions were often the exception. Settings lacking these systems imposed another layer of operational barriers on sampling. For example, some WES teams had to sample from open drains, canals, septic tanks or informal discharge points. These approaches allowed some form of surveillance to continue but were often described as labour intensive, logistically demanding and unlikely to produce representative data.

Digital infrastructure was also a weak link in surveillance systems. In many programmes, digital data platforms were either absent or fragmented. This delayed reporting and limited real-time communication among field teams, laboratories and public health authorities. In these ways, digital bottlenecks reduced the responsiveness and credibility of surveillance outputs.

“For the site collection we have ODK [software], where the supervisor enters data about the collection information that is processed by WHO. In our health system, we use DHIS2 [District Health Information System 2]. But these two are not connected; they are not interoperable. That is another challenge.”

– National public health officer, African Region, low- or middle-income country

In LMICs, infrastructure challenges defined both the scope and operational model of surveillance programmes. The absence of centralized wastewater treatment facilities outside capital cities or major urban centres forced programmes to rely on improvised sampling from surface water, canals or institutional discharge points. These gaps in the infrastructure intersected with inequities in surveillance coverage. Entire communities remained beyond the reach of WES activities – particularly those in slums, peri-urban areas or rural zones – due to the absence of formal sanitation or wastewater infrastructure. For some, this exclusion was seen as more than a technical limitation. It reflected how the dependence of surveillance systems on existing infrastructure reproduced broader health inequities. Stakeholders acknowledged that populations already underserved by public services were also those most likely to be unrepresented in surveillance data, raising concerns about the completeness and equity of the surveillance systems in general and WES in particular.

“Certain labs do not have all the capacities – staff or equipment – so we ship the samples to the central laboratory in [the capital city].”

– National public health officer, Eastern Mediterranean Region, low- or middle-income country

In these settings, infrastructure gaps intersect with weak transport networks, adding strain to field operations and restricting the geographical reach of surveillance activities. The scarcity of laboratory facilities outside urban centres further localized surveillance efforts, leaving large segments of the population unmonitored.

In some cases, WES provided an entry point for advocating for improved wastewater infrastructure. The activities of some WES programmes in these settings brought attention to neglected sanitation systems or opened dialogue with municipal authorities about expanding infrastructure in underserved areas. The general situation remained one of programmes adapting to the constraints of existing infrastructure, but with limited prospects for influencing systemic change in the short term.

In HICs, WES activities were generally supported by established infrastructure. These included centralized sewage systems that provided accessible and standardized sampling points in most urban areas. However, there were some blind spots, particularly in rural communities, in areas with decentralized sanitation systems or in isolated institutions. In these instances, WES programmes developed targeted sampling strategies to reach these populations and these often required additional coordination and investment. Even with more supportive infrastructure overall, stakeholders acknowledged that integrating these underserved areas into national surveillance frameworks remained challenging and resource intensive.

The challenges of digital infrastructure were not confined to LMICs. In various HICs, there were delays in data flow, limited integration between field and laboratory data systems, and an absence of real-time reporting mechanisms. These digital gaps were often underestimated in surveillance planning but became highly visible once programmes moved from the pilot to the routine phase.

Across both low- and high-income contexts, stakeholders tried to achieve a balance between working within the constraints of existing infrastructure and striving for broader, more equitable coverage of surveillance. Examples of such efforts included using mobile sampling teams and collaborating with municipal sanitation

services to identify alternative collection sites. While these adaptations allowed programmes to function under constrained conditions, stakeholders consistently emphasized that these approaches remained workarounds rather than long-term solutions. Nevertheless, some stakeholders considered emerging partnerships with municipal service providers, cross-sectoral collaboration and integration with urban planning as potential avenues to begin addressing systemic infrastructure barriers.

3.3.4 Logistical challenges

Stakeholders reported that the implementation of WES faced four interdependent logistical challenges, namely access to collection sites, sample transport and cold chain management, as well as the management of field supplies.

In LMICs, access to sample collection sites posed a significant operational challenge. WES teams often collected and transported samples using improvised means: personal vehicles, borrowed equipment or with support from local development partners. They faced persistent obstacles, including difficult terrain, seasonal road inaccessibility, and long distances between sampling sites and laboratories.

Once samples were collected, transport and cold chain management emerged as the next constraints. The timely and temperature-controlled transfer of samples, necessary to preserve sample quality, was not consistent owing to the constraints of difficult terrain and problems with transport. Weak coordination between ministries, local authorities and laboratories introduced further disruption to operations, causing inconsistent sample pick ups and deliveries, and delays in sample processing. These conditions limited the geographical coverage of WES and hindered the use of regular surveillance cycles. Implementation in these settings faced specific material management constraints, namely difficulties in procuring and restocking essential supplies, customs delays and limited options for suppliers. WES programmes faced challenges in ensuring the consistent availability of basic sampling materials, such as containers, disinfectants and personal protective equipment. Some programmes experienced frequent stock outs, forcing teams to delay or reschedule collections or borrow materials from other services. These disruptions undermined

adherence to routine collection protocols, affecting data comparability and adding to operational strain.

In HICs, logistical issues were less common, but still relevant, particularly when programmes expanded to new jurisdictions, rural areas or non-networked sanitation systems. In these contexts, the absence of established collection routes and workflows led to coordination challenges between agencies. The results were uncoordinated sample collection and laboratory backlogs. Even where automated samplers and digital tracking tools were available, WES teams noted that alignment between stakeholders was not optimal for ensuring timely sample deliveries, especially during surge periods.

3.3.5 Knowledge gaps in interpreting data

Implementing teams identified four interrelated and mutually reinforcing challenges in the gaps about knowledge of WES:

- Gaps in understanding, interpreting and contextualizing WES signals;
- The complexity of estimating the size of the population contributing to the sampled wastewater;
- Uncertainty about the best methods of communicating evidence to various stakeholders; and
- Lack of clarity about approaches for aligning evidence from WES with data from clinical or syndromic surveillance.

Stakeholders across settings observed that WES is an evolving practice and efforts are ongoing to enhance the interpretation and use of the data generated. While the capacity to generate data had strengthened, gaps remained in fully understanding, interpreting and contextualizing signals within diverse operational and epidemiological environments.

The researchers interviewed observed various degrees of heterogeneity in interpreting and understanding WES data across teams and institutions. Even when working with the same data, teams could arrive at different conclusions regarding the significance or implications for action. The researchers described this variability as an acknowledged feature of current practice,

shaped by differences in institutional experience, analytical tools and public health priorities. Several stakeholders noted that while some decision-making teams had become more familiar with data from WES, others remained cautious about using it. This reflected uncertainties around how to integrate WES outputs with those from other surveillance systems to enable holistic interpretation.

Another factor that posed a challenge to interpreting WES data was difficulty in estimating the size of the population contributing to the samples collected. Few countries had comprehensive mapping of their sewage system routes and precise information about the catchment population served by individual sampling sites. The researchers explained that reliable estimations could be made only in a few countries where sewage networks were highly developed and well regulated, and effectively prevented rainwater infiltration, thus ensuring that the system carries only sewage. Even in these settings, interpretation remains complex and subject to multiple variables, including variations in pathogen shedding rates and environmental factors.

In programmes in which WES was implemented at a smaller geographical scale, such as at the level of buildings or defined residential blocks, the capacity to interpret data improved due to clearer knowledge about the contributing population. However, participants expressed concern that such granular implementation remained the exception, with most programmes operating at broader municipal or regional scales, where population estimation and sewage network complexities introduced significant interpretive uncertainties.

“But what you notice is that the sensitivity of that early warning signal is higher at a more localized level.”

– National public health officer, European Region, high-income country

In some cases, these limitations on interpretation contributed to delays in decision-making, hesitancy about using the data or underutilization of evidence from WES. While WES was viewed as a useful additional information stream, the use of data from it was often constrained by ambiguity about

interpreting the data and uncertainties regarding how results should inform actions. Another common concern among researchers was how to communicate evidence from WES to non-technical audiences. There were difficulties in presenting complex environmental data in formats that were accessible to decision-makers without compromising accuracy. The situation was worsened by the lack of consensus about what defined a strong or actionable signal. This ambiguity further hindered effective risk communication. Without clear thresholds or standardized metrics, different stakeholders interpreted the same data in inconsistent or conflicting ways.

“It hasn’t been an easy road to go from wastewater signal incorporation into modelling and then actually having that output being understood by decision-makers in the public health agency.”

– Academic/researcher, Region of the Americas, high-income country

Several programmes reported challenges in aligning evidence from WES with clinical data or data from syndromic surveillance. Wastewater trends did not always align with case reporting, leading to uncertainty regarding which data stream should guide decision-making. In the absence of integrated frameworks for interpreting the data, some decision-makers reportedly questioned the reliability of WES data or used it primarily for retrospective review rather than as a source of real-time information.

Participants from public health authorities expressed a need for support in interpreting the data, including technical guidance, decision-support tools, training and visualization resources. While some materials that were developed during the COVID-19 pandemic were acknowledged as being helpful, these were perceived as having limited value in broader application to other pathogens and contexts. Thus, uncertainty about interpretation emerged as a significant barrier to system integration.

Stakeholders from LMICs had limited technical and conceptual capacities to interpret WES data.

This reflected how many teams were relatively new to WES, with basic training still in development, including both technical training and training in interpreting the data. International partners sometimes supported early implementation, but national institutions have not yet developed the local capacity to analyse and contextualize data independently. A common skill gap identified in these settings was limited competence in epidemiological modelling among researchers involved in WES.

In HICs, the main challenge was the lack of standardization and harmonization of tools for analysing and interpreting WES data. While analytical tools, statistical models and historical data were available, difficulties persisted in defining shared metrics, comparing results across jurisdictions and setting consistent thresholds for action. There were concerns about occasional misunderstandings or overinterpretation of evidence from WES that could create a lack of trust among decision-makers unfamiliar with the limitations of some methods or the context-specific factors influencing data quality.

3.3.6 Workforce capacity challenges

Workforce capacity emerged as an important limiting factor in the implementation and sustainability of WES. Implementing teams described the required workforce for WES as inherently multidisciplinary. It required field sampling teams, laboratory technicians, environmental surveillance officers, site selection personnel, data analysts and public health professionals.

In LMICs, the challenge of workforce capacity was characterized by systemic shortages of skilled personnel, coupled with limited institutional mechanisms to develop and retain these personnel. Many teams operated with limited staff and commonly reported shortages in staff with specialized skills in laboratory analysis and data interpretation. Staff turnover was high, commonly resulting from a combination of high attrition rates and lack of job security, owing to temporary contracts. This situation created additional challenges in terms of retaining institutional knowledge and sustaining operations. In these settings, environmental surveillance teams for poliovirus were seen as offering an interim solution

to address immediate staffing gaps. Also, recruiting skilled personnel, such as molecular biologists and data scientists, remained particularly difficult for countries due to competition from the international job market, and staff may have limited access to relevant academic or vocational training pipelines.

“It also requires capacity building....

Most of the [country’s] services are good in the use of clinical data, but there are environmental data. It’s a new area....You need to reorient people.”

– Academic/researcher, African Region, low- or middle-income country

In HICs, challenges in workforce capacity were less frequently described as fundamental shortages and more often reflected specific constraints encountered during expansion or surge periods. Stakeholders noted that during the COVID-19 pandemic, programmes had to rapidly scale up sampling and processing, often without time to recruit or train new staff. While basic institutional capacity existed, the pressure to expand quickly revealed gaps in surge staffing models, cross-training opportunities and flexible deployment frameworks. In a few cases, laboratory backlogs or reporting delays were directly attributed to a short-term lack of personnel during emergency periods or to limits on hours spent analysing WES samples.

Even in HICs, there were shortages of personnel with experience that bridged the environmental and epidemiological domains. As programmes began to collect high-resolution data – sometimes including from genomic sequencing, and subsewer and shed sampling – demand grew for expertise in data modelling, bioinformatics and cross-disciplinary interpretation. Several WES teams acknowledged that personnel had to learn these skills on the job, often with limited formal support or structured learning opportunities.

3.3.7 Governance and policy challenges

Governance and policy frameworks played significant roles in shaping the development, implementation and sustainability of WES

programmes. The presence or absence of formal mandates, regulatory frameworks and institutional coordination mechanisms influenced not only the initiation of surveillance activities but also their operational integration into existing public health and environmental systems. Governance was often interlinked with funding stability, data ownership and clarity about institutional roles, with implications for both the continuity and legitimacy of WES activities (Box 4).

A recurring theme across contexts was the lack of defined leadership and ownership of WES, particularly given its position at the intersection of public health, environmental management and water infrastructure. Stakeholders reported that this ambiguity led to fragmented responsibilities without overarching structures to ensure alignment, in which field collection might be overseen by environmental authorities or utilities, laboratories were housed in academic or research institutions, and data interpretation was conducted separately.

Research centres and universities were frequently the drivers of WES initiatives, particularly during the COVID-19 pandemic. However, they remained largely excluded from formal governance bodies, public health surveillance steering committees or decision-making platforms. While these actors generated data and conducted analyses, they lacked institutional authority to drive response actions or influence policy development. This created silos in which data remained within academic or technical domains, limiting its use in real-time decision-making or public health planning. In some countries, multiple WES programmes operated concurrently, often without coordination. Academic institutions, regional governments, ministries of health, and ministries of the environment each ran separate WES activities, focusing on different pathogens, geographical areas or surveillance objectives, without formal mechanisms to harmonize data, align strategies or share resources. Stakeholders suggested that these parallel tracks created false competition, gaps in coverage and inconsistencies in data interpretation, particularly when programmes operated with different methodologies or reporting timelines.

“Another challenge is stakeholder engagement. In [country], we started from scratch, without prior [poliovirus] surveillance. Convincing stakeholders, including ministries, to grant data access was difficult.”

– Academic/researcher, African Region, low- or middle-income country

When WES was led by institutions outside a ministry of health – such as a ministry of the environment or an academic body – there were consistent challenges in ensuring that the data were used to inform public health decision-making. The absence of structured protocols for sharing data or interagency coordination mechanisms limited the ability of ministries of health to use WES data systematically for health planning and emergency responses.

In addition to institutional fragmentation, experts in other surveillance domains – including clinical surveillance, epidemiology and virology – were not consistently consulted about or engaged in WES governance. Their limited participation weakened the potential for triangulating findings from WES with clinical and syndromic data streams. In turn, this hindered the broader integration of WES into public health surveillance systems.

In LMICs, governance and policy challenges were often fundamental. In many of these settings, WES activities were frequently initiated in response to emergencies, such as the COVID-19 pandemic, without the concurrent development of policy frameworks to support their sustainability. During an emergency implementation, responsibilities were distributed across multiple ministries, including health, environment and higher education, none of which had a clear mandate or legal authority to lead. This institutional fragmentation was compounded by limited policy advocacy, a lack of political prioritization and a reliance on informal partnerships with external actors. These gaps left WES initiatives vulnerable to discontinuation and limited their inclusion in routine health planning and budgeting.

In HICs, governance challenges focused more on alignment and harmonization with existing systems. WES often existed within broader environmental or health policy frameworks but was not clearly integrated into established surveillance systems. Environmental agencies and public health departments had their own separate data systems, risk thresholds and institutional priorities. This slowed data flow, integration, joint interpretation activities and communication. Thus, the use of WES data for decision-making was limited even in systems with established technical capacities.



Box 4. Poops.NZ: tracking COVID-19 in wastewater, the New Zealand experience

The New Zealand Institute for Public Health and Forensic Science, a Government-owned research organization, developed and operationalized a national wastewater surveillance system to monitor SARS-CoV-2 during the COVID-19 pandemic. This system integrates multiple data streams, semiautomated processes and geospatial analysis to inform public health responses outside the traditional framework for notifiable diseases.

During the initial phases of implementation, most of the data were collected manually, especially the flow rate at sample collection sites. Over time, processes have been streamlined and become semiautomated, requiring manual interventions only when there are reported issues with the data.

Three main data points were identified for the WES information system: laboratory test results, flow rate at collection sites and the reference population at the collection sites. When SARS-CoV-2 is identified in samples, these data are recorded using the STARLIMS platform and linked to a downstream analytics pipeline. REDCap was introduced to collect data about flow rates, and it utilizes twice-weekly automated email templates from sampling sites. Data about the reference population for the catchment areas are mapped using information from GIS and meshblock units, which are the smallest geographical reference units.

Automated pipelines integrate these three core data streams to produce standardized epidemiological metrics, including the number of genome copies per litre and genome copies per person per day. The data are visualized on the public access dashboard known as Poops.NZ, alongside COVID-19 case data generated by the EpiSurv platform, which is a centralized database in which all cases of notifiable diseases are collected, stored and managed (<https://episurv.esr.cri.nz/>). In addition, comprehensive weekly reports are generated and shared with the Ministry of Health.

Standard data validation procedures are utilized wherein any changes to the data require source-level edits with valid justifications. The system is built and hosted in-house, is not open source and plans are underway to migrate it to the cloud.

This electronic wastewater surveillance reporting system for SARS-CoV-2 provides a valuable tool for tracking trends in COVID-19, enabling early detection and trend analysis, and informing public health decision-making. It represents a scalable model for integrating environmental surveillance with public health infrastructure and offers a roadmap for similar programmes globally.

3.3.8 Ethical challenges

The main ethical concerns that stakeholders raised included:

- The sensitivity of data for certain communities;
- Issues around privacy and consent, especially when targeting small catchment areas, such as a specific building;
- Dilemmas around data access and use, including difficulties in communicating uncertain findings; and
- Concerns about equity in that WES systems might unintentionally exclude certain communities.

Stakeholders also noted there was generally a lack of specific formal frameworks for the ethical governance of WES, and many programmes operated without formal ethical review. Contextual differences were observed, with LMICs focusing more on community engagement and broader external influences, while HICs were more concerned with the legal, procedural and reputational aspects, such as public trust and institutional credibility.

Overall, stakeholders agreed there was growing recognition that ethical considerations are becoming increasingly important as WES expands, and formal ethical frameworks should be developed to ensure WES systems are socially responsible and transparent.

3.4 Requirements of end-users for integrating WES into digital tools

3.4.1 Ongoing digitalization efforts

Digital public health surveillance systems across WHO Member States are diverse, reflecting variations in infrastructure, capacities and policy priorities. The digital surveillance tools used by Member States each serve multiple but related functions in the surveillance cycle, such as case notification, laboratory management, and data collection and visualization.

Stakeholders observed that digital tools are

increasingly used for WES; for example,

- WHO's Surveillance Warehouse Database integrates wastewater data with public health systems, but requires modifications for emerging data types;
- WHO's Polio Information System (POLIS), is a proprietary repository that centralizes poliovirus surveillance data;
- The Environmental Surveillance Catalog (Novel-t, Enschede, Netherlands) stores information about environmental surveillance sites; and
- The Blue Line feature in Esri environmental surveillance (Redlands, CA, USA) maps wastewater drainage patterns.

3.4.2 Characteristics of digital surveillance systems and potential for integration

Stakeholders identified three mutually reinforcing characteristics of digital surveillance tools and platforms that have influenced their adoption by Member States (Table 1). These were the accessibility of source code (i.e. open source versus proprietary), whether there was national ownership and flexibility for including modules (i.e. modularity). Open source tools, such as the DHIS2, the WHO and Global Outbreak Alert and Response Network's Go.Data application, and the Surveillance Outbreak Response Management and Analysis System (SORMAS), allow customization to meet specific public health needs. Conversely, proprietary systems often pose challenges related to interoperability, data access and the cost of subscriptions for licenses.

Table 1. Digital surveillance tools used by WHO Member States

Digital platform	Function	Accessibility	Examples of users	Flexibility to add new modules
ArcGIS applications with Blue Line feature (https://www.arcgis.com/apps/webappviewer/index.html?id=9db-171b988c541f99cb-098dd849dafcf)	Mapping of wastewater drainage patterns	Proprietary, Esri	WHO African Region	Moderate
ArcGIS Survey123 (https://survey123.arcgis.com/)	Data collection and mapping	Proprietary, Esri	Public health agencies and researchers	Limited
Azure cloud services (https://azure.microsoft.com/en-us/get-started/azure-portal/)	Centralized data storage and processing	Proprietary, Microsoft	Federal level, such as the Canadian Ministry of Health	Supports modular expansion
DHIS2 (https://dhis2.org)	Health information management	Open source	Federal level, such as ministries of health; WHO African Region	High
Environmental Surveillance Catalog (https://es.world/en/catalog?view=map)	Repository for locations of environmental surveillance sites	Publicly available	WHO African Region	Moderate
EpiSurv (https://episurv.phfscience.nz/)	Case notification and public health reporting	Proprietary, New Zealand Institute for Public Health and Forensic Science	National level, such as the New Zealand Ministry of Health	Transitioning to cloud to improve modularity
GitHub (https://github.com/)	Open access data storage and data-sharing	Open source	National level, such as the New Zealand Ministry of Health	Highly flexible for adding new data sets
Magpi (https://www.magpi.com)	Mobile data collection, surveys, GIS-based mapping	Proprietary, Magpi	WHO African Region	Limited

Digital platform	Function	Accessibility	Examples of users	Flexibility to add new modules
ODK (https://getodk.org)	Mobile data collection, environmental surveillance	Open source	WHO Member States	High
ODM framework (https://www.cdisc.org/standards/data-exchange/odm)	Data standardization and interoperability	Open source	Federal level, such as the Canadian Ministry of Health of	Supports tracking of new pathogens
POLIS (https://extranet.who.int/polis/Account/Login)	Centralized data repository for poliovirus surveillance	Proprietary, WHO, GPEI	WHO headquarters and Member States	Moderate
Power BI (https://www.microsoft.com/en-us/power-platform/products/power-bi/)	Trend analysis and visualization	Proprietary, Microsoft	Some municipal health agencies, for example in Canada	Limited by licensing constraints
R Shiny applications (https://shiny.posit.co/r/getstarted/shiny-basics/lesson1/)	Data validation, standardization, and automated reporting	Open source	Public and research institutions	Highly flexible for adding new modules
REDCap (https://project-redcap.org)	Data collection for flow rate	Open source	National Institute for Communicable Diseases, South Africa	Highly customizable
SORMAS (https://sormas.org)	Surveillance and outbreak management	Open source	National level, such as the Ghana Health Service	High
STARLIMS (https://www.starlims.com)	Laboratory information management	Proprietary, Francisco Partners	National level, such as the New Zealand	Limited customization
Surveillance Warehouse Databasea	Integrates wastewater surveillance data with national public health systems	Proprietary, WHO	WHO, National Institute for Communicable Diseases, South Africa	Moderate, designed for national integration but requires modifications for new data types

Digital platform	Function	Accessibility	Examples of users	Flexibility to add new modules
Tableau (https://www.tableau.com)	Data visualization and dashboards	Proprietary, Salesforce	Federal level, such as the Canadian Ministry of Health	Moderate customization
WebIFA (https://novel-t.ch/projectdetail/webifa/)	System to integrate surveillance and lab data	Proprietary, WHO, GPEI	WHO African Region	High
WHO Europe Information System for Immunization Surveillance (known as WISE) ^a	Surveillance for vaccine-preventable diseases	Proprietary, WHO European Region	WHO European Region	Moderate
xMart (https://data.who.int/about/data/whdh/xmart)	Data exchange and integration	Proprietary, WHO	WHO	

DHIS2: District Health Information System 2; GIS: geographical information system; GPEI: Global Polio Eradication Initiative; ODK: Open Data Kit; ODM: Operational Data Model; POLIS: Polio Information System; REDCap: Research Electronic Data Capture; SORMAS: Surveillance Outbreak Response Management and Analysis System; WebIFA: Web Information For Action; WHO: World Health Organization.

^aThis system does not have a public URL.

Ownership of surveillance systems and data played crucial roles in determining how stakeholders managed, protected and shared data. Member States that had greater control over their systems established robust data-sharing policies and security protocols that aligned with their national public health priorities. Further, stakeholders considered the flexibility of the system for integrating new modules. The ability to adapt systems to emerging public health needs, including to account for WES data, is gaining increased consideration when choosing digital tools. While most Member States had a principal digital system for public health surveillance, they commonly adapted multiple digital tools to accomplish additional tasks in different contexts (e.g. outbreak response) and settings (e.g. areas with limited or unreliable internet connectivity).

3.4.3 Current workflows

Few Member States have documented workflows for WES. While some workflows have been captured in academic publications and project-specific reports,

comprehensive SOPs and detailed flowcharts are scarce for viruses beyond poliovirus and SARS-CoV-2.

In some LMICs, early environmental surveillance efforts transitioned from manual, paper-based approaches to digital data collection using the ODK platform. However, formal SOPs that document how these transitions should be made remain limited. The ECDC is working on integrating data from wastewater surveillance into infectious disease surveillance, yet a standardized workflow has not been widely disseminated. Some HICs have well documented WES programmes, but their methodologies vary based on regional public health priorities and infrastructure.

3.4.4 User personas for digital modules

User personas refer to the distinct categories of system users, each representing a specific role, responsibilities and access rights within the platform. They represent the different stakeholders in public health surveillance and outbreak response for whom the system is designed, ensuring that

the workflows, dashboards, and permissions are tailored to their tasks. Despite the lack of universally adopted workflows and guidelines, some Member States have developed internal SOPs for sample collection, laboratory processing and data reporting. This analysis identified the workforce categories that play key roles in WES, including surveillance supervisors, epidemiologists, laboratory scientists, data managers, field officers and community sanitation workers. These categories represent the user personas that are key to developing a digital module for WES that complements existing surveillance systems. These roles interact at different levels, ensuring an integrated approach to disease surveillance, environmental monitoring and public health decision-making.

The expectations of end-users were that a documented, task-based workflow would integrate several components of the public health surveillance process, including:

- Environmental sampling;
- Sample packaging and transportation;
- Sample storage and recovery;
- Laboratory analysis;
- Data visualization with digital tools;
- Interpretation of results;
- Compilation of reports; and
- Dissemination to stakeholders through established and secure communication channels.

Stakeholders expect such a workflow to:

- Outline the sequential stages of analysis and the tasks;
- Specify the roles and responsibilities of various user personas;
- Map the interactions and dependencies among users and tasks;
- Assign user access rights (e.g. read only, edit, share), based on their roles and responsibilities; and
- Incorporate decision-making processes at appropriate stages of task execution.

End-users identified critical decision points that include scenarios such as the mislabelling of samples, assessing the condition of samples both at the collection site and upon arrival at the laboratory, and assessing sample integrity before laboratory analysis. Additional decision nodes would address how to handle outlier results and the procedures necessary for repeat testing, as well as how to identify instances requiring data normalization to ensure accuracy in interpreting and reporting data.

3.4.5 Minimum set of data types for a digital module

Based on the expected workflow for WES, end-users identified the broad categories of data types required to develop a basic digital WES module (Annex 7). These categories begin with the accurate identification and characterization of sampling locations, including the use of geographical coordinates and comprehensive descriptions of locations. Each site should be distinctly named and catalogued to ensure consistency and ease of reference.

End-users described the need for sampling and transportation protocols that specified the type of sample collected, whether a grab or composite sample, and included details about composite sampling methods and the duration of sampling. Variables such as the wastewater flow rate and sample condition upon arrival at the laboratory are expected to be captured to closely monitor sample integrity and the reliability of sampling. End-users emphasized that data about laboratory processes should include information to aid in traceability. The required data fields for laboratory analysis should include the date of analysis, technician identifiers and a dropdown field for standard analytical methods, with free text fields for recording important notes. This type of approach would ensure methodological consistency and the reliability of laboratory results. Participants emphasized that the integration of WES data with clinical and epidemiological data was critical for tracking clinical cases within catchment areas and would enhance the public health relevance of WES.

End-users expected that quality assurance would be a key consideration when designing a digital module for WES. They suggested that stringent

data validation procedures should be incorporated to enhance data quality and the reliability of the evidence produced. These quality assurance measures should include both automated validation checks and manual verification to address issues such as duplication, field validation and missing data. They expected that data visualization and reporting would be supported by automatically generated reports and the use of dashboards, enabling the timely, transparent and actionable communication of results.

End-users, especially those from HICs, emphasized the need for the digital tool to maintain a strong focus on ethical and regulatory compliance. Special attention is expected to be paid to data privacy, particularly in the handling of geographical coordinates and settlement identifiers, to uphold ethical standards and adhere to regulatory requirements.

3.5 The path forward for embedding into routine public health surveillance

3.5.1 Future plans for implementation

Stakeholders shared plans and aspirations for their programmes and countries. These included plans for scaling up, and considerations for scaling down, institutionalization, capacity-building, and research and innovation.

3.5.1.1 Rightsizing implementation for each context

Overall, the dominant trend was that most programmes were scaling up, or preparing to scale up, as resources and opportunities aligned. Stakeholders described scaling up in four operational dimensions, namely geographical scale, the scope of surveillance targets, the transition to routinization, and the level of institutional integration and participation.

i. **Scaling up geographical coverage:**

Geographical expansion was frequently mentioned as an area in which programmes saw value in extending coverage beyond the initial sites, which were often in capital cities or urban

centres, to include rural, underserved or high-risk areas. However, stakeholders emphasized that such expansion required substantial capacity-building efforts, particularly in LMICs.

“We are building capacity now, and the idea is that in the next phase, this can be scaled nationally with government support.”

– National public health officer, African Region, low- or middle-income country

ii. **Scaling up the scope of surveillance:**

Stakeholders also described scaling up as involving broadening the scope of surveillance targets. Some stakeholders expressed intentions to move beyond surveillance for SARS-CoV-2 to incorporate other pathogens, such as norovirus, hepatitis A virus or markers of AMR. They framed the expansion of pathogen detection as part of evolving WES into a more versatile and integrated platform.

“The goal is to develop a tool specific for each pathogen present, to be ready to implement surveillance in [country].”

– International organization

iii. **Scaling up from event-driven to routine surveillance:**

Several stakeholders also highlighted as essential dimensions of scaling up the need to increase sampling frequency or transition from event-driven testing to routine, continual monitoring. They described these changes as necessary to support early warning systems and maintain system readiness between outbreaks.

iv. **Scaling up integration and institutional participation:**

Stakeholders explained that scaling up was also conceptualized as enhancing institutional integration and participation. They emphasized the need to more systematically involve local governments, environmental authorities and regional laboratories. They described these efforts as necessary for creating more distributed, resilient and sustainable surveillance systems.

“Now our goal is to institutionalize wastewater surveillance into national epidemiological systems.”

– National public health officer, European Region, high-income country

Across these dimensions, stakeholders consistently emphasized that scaling up required not only technical and operational readiness but also sustained political will, a formal roadmap and dedicated financial resources. Several noted that while ambitions to scale up were present, the absence of these enabling factors often slowed progress or led to cautious, opportunistic expansions rather than systematic efforts to scale up programmes.

Very few programmes had scaled down, and even among those that had, reductions were framed as reactive or temporary rather than permanent. Some programmes were described as being in a holding pattern – that is, reduced from their peak operations but maintaining core capacity and remaining ready to scale up again. When scaling down was discussed, it was often framed as a reactive response to systemic vulnerabilities, rather than as an actively pursued operational objective.

“We de-escalated the number of sampling sites and time frame for sampling because of the lack of finances....The funding from the [government] is a little bit more limited compared to [that from] external partners.”

– National public health officer, European Region, high-income country

Scaling down was understood to involve the phasing out of specific components, reducing geographical or technical scope, or transitioning systems to a more limited or background mode. While adjustments might be necessary over time, the prevailing focus remained on maintaining as much surveillance capacity as possible.

Stakeholders explained that future reductions in programmes could occur in response to specific triggers, including:

- The withdrawal of external funding;
- A decline in political attention; or
- Reductions in perceived public health urgency.

Stakeholders from programmes that initially expanded during the COVID-19 pandemic noted that some reductions in scale might be necessary once pandemic urgency subsided, particularly where systems lacked dedicated budgets or national strategies to sustain operations at peak levels (Box 5). However, these considerations were often framed more as concerns than concrete plans.



Box 5. Challenges in sustaining wastewater surveillance programmes: the case of Ontario, Canada

Ontario's wastewater surveillance programme was one of the largest in Canada, covering more than 120 locations and monitoring multiple respiratory viruses, including SARS-CoV-2, respiratory syncytial virus and influenza virus. The programme provided epidemiological insights, with results being directly communicated to all public health units across the province during the COVID-19 pandemic. However, in July 2024, despite its demonstrated benefits, the programme was discontinued due to funding constraints and jurisdictional shifts.

Key challenges to the programme were the lack of long-term financial planning and the programme's lack of integration into public health systems. The programme was initially funded by the Ministry of the Environment, Conservation and Parks rather than the Ministry of Health, a decision made to address immediate needs during the COVID-19 pandemic. However, because it was not embedded within the ministry responsible to the health care system, the programme lacked a clear mandate for continuation. While the federal government expanded its wastewater surveillance initiatives, the anticipated transition of financial responsibility from the province to the federal level did not materialize, ultimately leading to the programme's termination.

Beyond funding, another major issue was that the programme was not designed from the outset to be action oriented. Rather than being built to directly support public health interventions, it was initially focused on collecting data and assessing the feasibility of wastewater surveillance. This resulted in limited integration of wastewater surveillance data with public health assessments and tools, making it harder to justify continuing investment once emergency funding declined.

“The programme in Ontario....was built to understand whether and to what degree wastewater surveillance tracks SARS-CoV-2 across the province, which is quite different to building a programme designed to provide public health benefits...[and] the initial, limited goal of the programme [was] ultimately not enough to sustain it.”

– Robert Delatolla, Director, Wastewater Surveillance Research Group

Ontario's experience highlights the importance of structuring wastewater surveillance programmes to support public health utility from the beginning as opposed to providing data to public health services without a clear plan for its integration. Efforts that clearly demonstrate their actionability, such as Ottawa's wastewater surveillance system, which is

directly integrated into the city's respiratory health risk assessment tool, have been sustained through municipal and hospital funds. Additionally, programmes must engage public health stakeholders early, ensuring that data are not only collected and disseminated to public health but also that there is a clearly defined plan for how the data will be actively used to inform health decision-making.

“Building a wastewater surveillance programme to address critical health system needs and gaps identified by public health practitioners and policy-makers would reposition wastewater surveillance to provide benefits to the province and save the province funds.”

– Robert Delatolla, Director, Wastewater Surveillance Research Group

3.5.1.2 Research and innovation

The value of research and innovation was generally acknowledged among stakeholders across settings and disciplines. However, they differed regarding whether research and innovation were positioned as active priorities within a system, as emerging needs or as aspirational concepts. Some stakeholders described clear, ongoing or planned research activities, while others referenced research and innovation more passively – that is, as desirable but secondary to immediate operational needs. This divergence reflected both a system's maturity and the perceived proximity of research and innovation to stakeholders' immediate surveillance agendas.

Some of the stakeholders, mostly those from HICs, described research and innovation as an essential and actively pursued dimension of their surveillance systems. They referred to research agendas, ongoing studies or planned changes to sampling methods, pathogen detection or data interpretation. Stakeholders in this group framed research as tightly linked to immediate surveillance challenges and needs, emphasizing the importance of generating context-specific evidence to guide surveillance design, optimization and policy alignment. However, even in these contexts, some stakeholders acknowledged that the positioning of research and innovation varied, and that during periods of operational strain or shifting public health priorities, these activities risked becoming deprioritized.

In LMICs, stakeholders generally described research and innovation as important but not yet central to their priorities for the surveillance system. While they recognized that methodological and technological innovations were needed, the dominant focus remained on establishing or consolidating basic surveillance operations. Stakeholders noted that the capacity, funding and institutional frameworks that would allow them to pursue structured research agendas were limited, and in many cases research activities depended on partnerships with academic or international research institutions. Some stakeholders acknowledged ongoing or planned studies, but these were often described as externally driven or donor-supported, rather than nationally owned or prioritized.

3.5.1.3 Capacity-building

Regardless of the maturity of a system or the resource context, stakeholders emphasized that developing and sustaining human and institutional capacity remained essential to ensure a system's responsiveness to new pathogens, shifting objectives and technological advances. They described capacity-building as involving multiple layers, including technical training for laboratory and field staff, the development of data management and interpretation skills, and the strengthening of capacities for institutional coordination and governance.

Stakeholders noted that scaling up surveillance activities placed new demands on systems, exposing gaps in capacities in logistics, sampling operations, data analysis and public health communication. Several stakeholders shared their experiences of capacity-building activities that had been expanded or adapted to support scale up and these included the decentralization of training to regional laboratories or the establishment of mentorship models to build local expertise.

Hence, stakeholders plan to continue adapting capacity-building to local contexts and needs, and they emphasized that training and support should not be limited to technical protocols but should also encompass practical problem-solving, operational adaptability and skills in cross-sector collaboration. Stakeholders plan to continue learning from one another's capacity-building models, recognizing that no single approach fits all systems and that approaches need to respond to local realities and workforce dynamics.

3.5.2 Stakeholders' insights on embedding WES into routine surveillance

Stakeholders were asked about and offered suggestions on five key areas for adopting and integrating WES into routine public health surveillance systems. These areas were policy support, funding, technical support, workforce capacity and stakeholder coordination.

3.5.2.1 Policy support

Against the current background of evolving legislative backing and mandates, WES often operated outside formal public health systems, leading to vulnerabilities when competing priorities emerged. Stakeholders proposed that adjustments should be considered for legal, regulatory and institutional frameworks to support, scale or formalize WES systems.

“We are working on appropriate legislation and protocols for handling sensitive data, especially regarding detection of illicit substances.”

– National public health officer, Eastern Mediterranean Region, high-income country

These suggestions were rooted in their experiences of navigating implementation gaps, managing ambiguities in institutional authority and identifying the broader need to secure WES within national public health strategies.

While the scope and drivers of policy change differed across contexts, stakeholders consistently positioned it as essential for ensuring WES could be institutionalized and maintained within national surveillance architectures.

3.5.2.2 Funding

Suggestions about funding models focused on how prevailing financial arrangements constrained the sustainability of WES. Most stakeholders worked within systems that were heavily reliant on short-term, project-based, or donor-driven, funding mechanisms. Based on these experiences, they made four mutually reinforcing suggestions.

i. Establish dedicated and proactive budget lines: Stakeholders strongly suggested that dedicated and proactive budget lines should be established within national or institutional funding structures. These budget lines were described as essential to ensuring routine, predictable financing that would allow systems to continue operating even during periods of low pathogen activity or outside of emergency contexts. Stakeholders were confident that

proactive budget allocations would allow WES programmes to function as stable, enduring components of national health systems, rather than as temporary, crisis-activated interventions.

ii. Establish contingency financing mechanisms: As part of strengthening preparedness for emergency responses, stakeholders suggested contingency financing mechanisms should be established that are capable of maintaining a stable baseline of surveillance year-round, while also allowing for a surge capacity to rapidly scale up during outbreaks or public health emergencies. This is particularly critical in LMICs, where funding is relatively unstable.

“We need dedicated funds for WES for pathogens beyond poliovirus. Government ownership and financial support are key.”

– National public health officer, Eastern Mediterranean Region, low- or middle-income country

iii. Incorporate transition and sustainability plans into implementation proposals: To give a new WES programme a better chance of surviving when donor support ends, stakeholders suggested including clear plans for sustainability to inform decisions about whether to approve implementation in the first place. Structured financing plans were seen as necessary to ensure the transition from donor funding to national funding mechanisms, and to provide a clear pathway for gradually shifting financial responsibility to domestic institutions while preserving a programme’s continuity.

iv. Establish multisectoral co-financing arrangements: Multisectoral co-financing arrangements involving the health and environmental sectors, and potentially other sectors, emerged as a viable strategy for buffering the unstable funding that is common in both low- and high-income settings. This step was described as particularly relevant in contexts where wastewater surveillance served multiple policy objectives, such as environmental monitoring, public health surveillance and urban planning.

3.5.2.3 Technical support

Stakeholders made suggestions about four closely related technical aspects of WES implementation, namely laboratory methods and workflows, standardization of laboratory protocols, quality control and support for interpreting data from WES.

i. Laboratory methods and workflows: Across contexts, stakeholders suggested it was important to develop faster, more affordable and scalable laboratory methods to reduce operational costs and enable broader expansion of programmes. They recognized that current methods are complex and resource intensive, which limited their applicability in routine settings, particularly in under-resourced programmes. They identified innovations in sample concentration techniques and improvements in detection sensitivity as key areas in which technical refinement was needed. The simplification of laboratory methods would then translate into a simplification of laboratory workflows. For LMICs and implementation of new programmes, stakeholders suggested that user-friendly diagnostic tools and ready-to-use sample processing kits would minimize reliance on highly specialized personnel and also increase throughput. Stakeholders in more advanced programmes, mostly in HICs, suggested investing in multiplex testing platforms that could simultaneously detect multiple pathogens or indicators from one sample, reflecting a drive towards more efficient testing strategies.

ii. Standardization of laboratory protocols: To reduce interlaboratory variability, researchers suggested harmonizing methods for sample processing and molecular analysis. Some researchers emphasized the need for validated, open-access protocols that could be adopted by emerging programmes without requiring significant resources. They viewed the dissemination of such protocols as essential to support a programme's equity and quality. They clarified that the call for harmonization was not a call to adopt a single methodology in all laboratories. Instead, harmonization would help increase transparency, contextual streamlining, and the development of methods for comparing results and interpretations.

iii. Quality control for laboratory methods:

Stakeholders also emphasized the need to strengthen quality control systems. This would include establishing routine calibration procedures, implementing SOPs for all analytical steps and advocating for rigorous documentation practices. These improvements were viewed as necessary to ensure data reproducibility and reliability, and acceptance of the data by stakeholders.

iv. Support for interpreting WES data: The ability to interpret data reliably emerged consistently as a weak link in the practice of WES. Stakeholders suggested that clear data interpretation frameworks and guidance documents should be developed to support public health officers and decision-makers in translating technical outputs into actionable public health information.

3.5.2.4 Capacity-building

Stakeholders across institutional, research and governmental entities suggested five strategies for building workforce capacity.

i. Develop structured training programmes:

Stakeholders suggested that structured training programmes should be developed that extend beyond introductory courses to include advanced laboratory methods, data interpretation and system management skills. They explained it was important to embed these programmes within institutional mandates to ensure their continuity and formal recognition.

ii. Decentralize workforce training: Stakeholders suggested that training efforts should be decentralized to ensure that workforce capacities are built at the subnational and local levels, thus supporting the scalability and resilience of surveillance systems. This suggestion included calls to implement a training-of-trainers model, enabling institutions to multiply internal expertise and reduce their reliance on external consultants. This approach was seen as a strategy that would foster institutional memory and promote the growth of autonomous capacity.

iii. Support workforce retention and the continual updating of skills: To support

workforce retention and the continual updating of skills, stakeholders suggested that capacity-building efforts could be framed as ongoing programmes rather than as isolated events. These approaches could include periodic refresher training, structured mentorship models, and the integration of WES competencies into public health and environmental science curricula. This would support the development of a sustainable workforce pipeline capable of adapting to evolving technical requirements.

- iv. Supplement workforce capacities with management and leadership training:** Stakeholders also suggested that capacity-building initiatives could expand beyond technical training to include skills in management, coordination and supervision. Strengthening these competencies was seen as essential to empower local teams to oversee and manage system operations independently, contributing to the institutionalization and ownership of WES programmes.
- v. Create and strengthen formal training partnerships with academic and research institutions:** For longer-term strategies, stakeholders suggested creating national training programmes in partnership with universities and training institutes to build in-country capacity. These efforts were positioned as essential steps for establishing self-sufficient workforces capable of supporting both routine surveillance operations and the introduction of emerging technologies.

3.5.2.5 Enhancing stakeholder coordination

The suggestions for stakeholder coordination focused on aligning contributions, responsibilities and data flows across diverse actors, including public health authorities, environmental agencies, laboratories, academic institutions, donors and those implementing programmes locally. Participants considered coordination to be necessary for ensuring that surveillance activities could function efficiently across technical, administrative and institutional boundaries.

- i. Designate leading institutions:** Stakeholders suggested that coordination efforts could be

guided by clearly designated lead institutions. These entities would assume responsibility for convening relevant stakeholders, organizing the exchange of information, ensuring the consistency of messaging, and overseeing the coherence of surveillance implementation across administrative levels and sectors. These steps were viewed as critical to preventing fragmentation, inefficiencies and unclear lines of accountability, particularly as surveillance systems expanded or introduced new technologies.

“We hope to have a...governmental body to have all kinds of these tests, the environmental tests regarding wastewater treatment, and wastewater input [and] output, besides having [WES testing] monthly, not on certain occasions.”

– National public health officer, Eastern Mediterranean Region, low- or middle-income country

- ii. Ensure early and continual stakeholder engagement:** Public health officials suggested that stakeholder engagement should begin early, during the design phase of surveillance programmes, and continue throughout implementation. They explained that this approach would build trust, clarify expectations and secure the commitment of all relevant actors to shared objectives and operational responsibilities.
- iii. Strengthen alignment with external partners:** In addition to internal coordination among domestic actors, stakeholders suggested strengthening alignment with external partners, donors and international organizations. They observed that establishing country-led coordination mechanisms would ensure that support from partners was harmonized with a country's priorities and delivered through local institutions. It was proposed that this might avoid parallel structures and promote sustainable ownership of surveillance systems.

iv. Develop shared data platforms: Stakeholders suggested that shared data platforms or tools should be developed to support coordination. These tools were seen as important for promoting transparency, reducing duplication of effort and enabling timely access to data by all relevant stakeholders. They were confident that such platforms could enhance both horizontal coordination between agencies and vertical coordination across administrative levels.

3.5.3 Sustainability and resilience

Stakeholders identified five interconnected factors that would enhance the sustainability and resilience of WES systems: funding models, country ownership, leveraging existing systems, integrating them with public health surveillance and prioritizing pathogens.

A public health officer from one LMIC emphasized that, “We can’t keep depending on donor funds”, underscoring how programmes in their country relied heavily on short-term emergency financing. Stakeholders plan to work towards diversified funding models that will draw from multiple domestic sources, although they acknowledged the challenge of coordinating across ministries and budget lines.

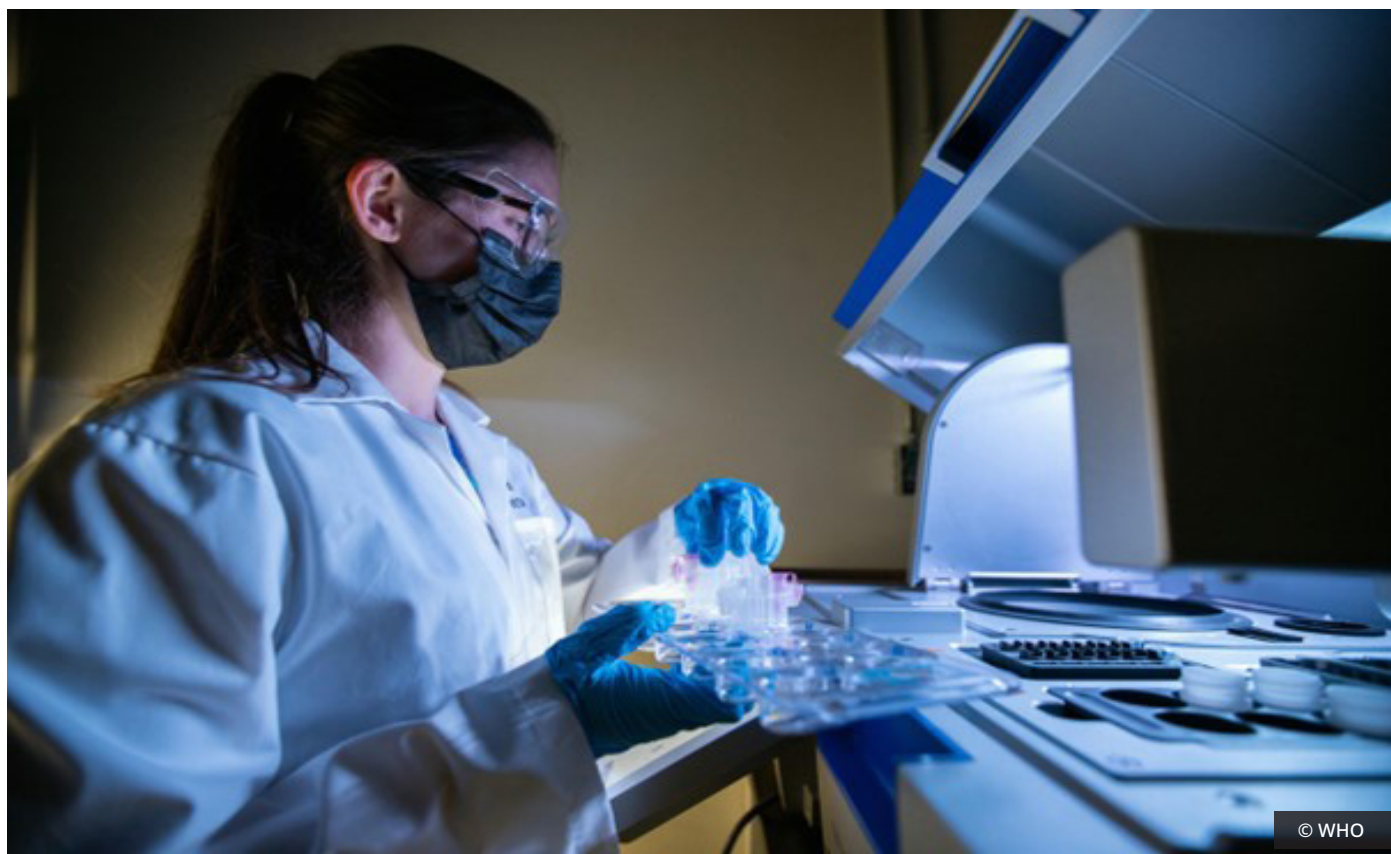
Stakeholders plan to step up advocacy for country ownership of programmes, explaining that it made the difference between temporary pilot projects and sustainable national systems. One public health officer from an LMIC explained, “We lack a clear national lead, so WES remains a side project, rather than a public health function”.

Stakeholders from government-led WES programmes noted that formal staffing structures and domestic budget lines helped ensure continuity. They plan to advocate for the government to take the lead in WES.

Stakeholders from both HICs and LMICs described how building on existing infrastructure – particularly poliovirus surveillance platforms and laboratory networks – enabled quicker WES implementation and reduced operational costs. As one participant from an LMIC stated, “We had a lab system ready from polio, and that really helped us hit the ground running”.

Stakeholders from all contexts saw value in exploring synergies with existing systems to enhance and sustain WES. Most stakeholders agreed that WES programmes will not survive if they stay in a silo and are not integrated with other systems. Integrating WES operationally and strategically requires aligning sampling, data analysis and reporting routines with national workflows, and including WES outputs in decision-making platforms.

The prioritization of pathogens emerged as one sustainability factor that stakeholders plan to tailor to their national capacities and resources. They recognized it was both a technical and political process. Several participants from LMICs admitted their selection of pathogens was driven by an outbreak response or donor focus, noting that they started with what they were told was urgent. In the future, they plan to transition to more structured, nationally driven prioritization through cross-sector consultative processes aligned with national public health goals.



Dr E. Mercier running wastewater and environmental samples, Canada, 2022 © Robert Delatolla

4. Conclusions and considerations

4.1 Conclusions

This qualitative global landscape analysis reveals insights into the complexities, opportunities and challenges inherent in implementing WES across diverse contexts. While strong momentum and considerable investment are driving WES forward, this analysis underscores that its long-term success depends on addressing persistent structural, operational and governance challenges.

4.1.1 Global interest is clear, but sustainability and scale up need stronger foundations

This analysis confirms that WES has attracted substantial global interest, with countries applying it at varying scales and scopes, and that programmes are at different levels of maturity. Implementation

ranges from targeted pilots and research initiatives to more formalized programmes integrated into national public health surveillance systems. This diversity reflects growing recognition of the benefits of WES, particularly for generating population-level insights in defined geographical catchment areas.

However, the variability in implementation signals that there is no universally established model for how WES should be operationalized. Strong governance frameworks, sustainable financing mechanisms, and systematic integration into routine surveillance and public health decision-making are critical. Without these, WES risks generating data that are disconnected from operational needs and underutilized. Aligning the scale and objectives of WES with the capacities of national systems is essential to ensure that it delivers actionable and sustainable value.

4.1.2 A valuable complement to public health surveillance

Across settings, WES is recognized as an addition to existing surveillance systems, offering flexible, scalable population-based monitoring that enhances situational awareness and supports the earlier detection of public health threats.

Stakeholders consistently described how it adds value, particularly in three main areas.

- First, it enables the early detection of emerging, re-emerging or rare pathogens that may evade detection through traditional clinical surveillance.
- Second, it helps to monitor the circulation and burden of infections in the population, particularly for diseases in which most cases are asymptomatic or mild. In such situations, case-based surveillance often underestimates true infection levels, whereas WES can detect population-level signals that reflect the overall circulation of pathogens.
- Third, in contexts with limited or no routine public health surveillance, WES offers a practical means of capturing minimum population-level signals that would otherwise be missed.

At the same time, stakeholders were clear that WES has well-defined functional limitations. It provides signals at the population level but cannot produce the case-specific information required for outbreak investigation or to select specific interventions. Its performance depends on the pathogen, relying on shedding dynamics that are not equally well characterized across diseases and on laboratory methods and analyses that vary in maturity. In its current form, WES is best suited to monitoring trends, detecting potential signals and supporting situational awareness. It cannot provide precise measures of incidence. Its value lies in complementing traditional surveillance, and its role is strongest when it is understood as part of an integrated, multisource surveillance strategy. Hopefully, future improvements in technology and analyses will help make WES a more robust public health tool.

Where domestic financing remains limited, WES

risks remaining outside of formal, more sustainably financed surveillance programmes and constrained by the timelines for donor-funded projects. While donor support has been indispensable for scale up, achieving sustainability will require stronger government ownership, clearer institutional commitments and the integration of WES into national budgets and core public health functions.

4.1.3 Its potential is recognized, but uptake for public health decision-making has been slow

While WES has been recognized as a promising tool for strengthening pandemic preparedness and response – particularly following its use for SARS-CoV-2 – the translation of data from WES into public health action remains limited. Stakeholders highlighted that in most contexts, data from WES are not systematically used to guide decisions or trigger interventions.

Key barriers include uncertainty about how to interpret data from WES alongside data from traditional surveillance indicators, and the absence of clear, actionable thresholds to inform timely responses. Many stakeholders also noted that there are few documented examples in which WES has directly informed public health action, reinforcing perceptions of it as an experimental or research-driven activity rather than an operational tool.

Until governments gain confidence in both the usefulness and cost-effectiveness of WES, it is unlikely to be integrated into routine decision-making processes. For now, WES is more commonly leveraged during emergencies and for donor-supported projects, rather than as part of sustained public health practices.

4.1.4 Translating WES data into public health action remains challenging

WES has demonstrated the ability to generate a substantial volume of data, capturing signals from diverse environments, pathogens and population catchments. This abundance is one of its defining strengths, offering population-level insights that are often difficult to obtain through routine surveillance alone, whether event- or indicator-based. Yet this analysis also highlighted a persistent challenge:

turning that abundance of data into actionable public health intelligence. Despite growing experience with WES, knowledge gaps remain significant across every step of the surveillance cycle, from data collection and data normalization to analysis, interpretation and the communication of results.

Even where sampling is routine and laboratory methods are robust, interpreting the data presents persistent challenges. Environmental variability, signal noise and a lack of standardized thresholds complicate efforts to extract actionable insights. Many programmes operate without historical baselines or established reference points, making it difficult to distinguish between expected fluctuations and true anomalies. In some cases, analytical capacity is limited; in others, the institutional pathways for using the data are ambiguous or underdeveloped. The absence of integration with other surveillance streams further hinders interpretation, reducing the ability to triangulate findings or contextualize them within broader epidemiological trends. Producing actionable insights requires more than just data collection: it demands sustained investment in interpretation and coordination, and in embedding WES into institutions. Without progress on these fronts, the full potential of WES as a decision-support tool will remain difficult to realize, particularly in contexts where public health authorities are cautious about acting on signals they do not fully understand.

4.1.5 Governance determines whether WES remains a project or becomes a public health asset

By its very nature, WES is a collaborative endeavour. It cannot be implemented by a single institution or sector. The success of WES depends on coordinated contributions beyond ministries of health, from public health authorities, environmental agencies, laboratories, academic partners and international organizations, since ministries are not the default and primary leaders in WES implementation. This diversity of expertise is one of the system's greatest strengths, allowing WES to operate at the intersection of public health, environmental management and laboratory science. But collaboration alone is not enough.

When institutions have clearly defined roles and responsibilities, collaboration is more likely to deliver reliable and sustainable surveillance systems. Formalizing these roles – through coordination agreements, governance structures and clear rules for data-sharing and ownership – helps WES systems run more effectively and connect more fully with broader public health surveillance efforts. When this collaboration is absent, even well-intentioned partnerships can become strained, with operational delays, inconsistent workflows or uncertainty about how data should inform public health action. Ultimately, the lesson is consistent: WES works well not simply because it is collaborative, but because such collaboration is anchored by shared accountability, clear processes and governance that aligns diverse actors around common goals.

4.1.6 Donor investment as a double-edged sword

Significant donor investment is currently driving much of the growth and expansion of WES. External funding has been instrumental in enabling implementation, supporting technical capacity and expanding surveillance coverage. In many contexts, donors' contributions remain essential not only for the initial deployment but also for ongoing operations, including laboratory testing, sampling activities and workforce development.

However, this funding model also presents challenges for long-term sustainability. Many programmes continue to rely heavily on donor-funded projects, which creates uncertainty about the ability to maintain operations beyond short-term funding cycles. This dependency affects workforce stability, infrastructure planning and whether WES is integrated into national public health systems. Where domestic financing remains limited, WES risks remaining outside of formal surveillance structures, constrained by a project's timelines rather than long-term national strategies. While donor support has been indispensable for scale up, achieving sustainability will require stronger government ownership, clearer institutional commitments and the integration of WES into national budgets and core public health functions.

4.1.7 Mixed perceptions of cost-effectiveness reflect both potential and actual constraints

WES presents a complex cost-effectiveness profile that is shaped both by its operational advantages and contextual constraints. As a population-level monitoring tool, WES offers substantial efficiencies through pooled sampling, the ability to detect multiple pathogens from a single sample and as a complement to testing individuals. These attributes can result in economies of scale and make WES a financially viable complement to traditional surveillance systems, particularly in large or densely populated settings and for sustained, long-term monitoring.

However, the cost-effectiveness of WES is not uniform across all implementation contexts. High initial capital investments – such as those required for laboratory infrastructure, training and digital integration – may limit its financial feasibility in resource-constrained or low-population settings where fixed costs are not easily distributed. Furthermore, the economic value of WES depends not only on its operational costs but also on the quality, interpretability and use of its outputs. In scenarios in which WES data are poorly integrated into decision-making processes, duplicated by existing systems or of limited actionable value, the return on investment becomes uncertain. Therefore, the cost-effectiveness of WES should be evaluated within the broader surveillance ecosystem by considering scale, integration and the usefulness of the data. While WES can offer significant economic advantages under the right conditions, its value depends on the context, which requires careful consideration during planning and implementation.

4.1.8 Growing attention to ethics

Alongside these operational and data-related challenges, the ethical dimensions of WES are also gaining increasing attention. Questions of privacy, data ownership and the responsible use of population-level data can no longer be treated as peripheral concerns. The recognition that WES operates at the intersection of public health, environmental monitoring and community-level data collection has elevated ethics from a background consideration to a core element of its

implementation. Growing awareness around the need to consider ethics is an encouraging step towards strengthening public trust and ensuring responsible surveillance practices.

While implementation rightly reflects local contexts, most countries are framing ethical questions as context-specific, even though the underlying ethical principles apply universally. In the absence of common WES protocols and standards, decisions are often based on internal protocols or informal practices, or adaptations of clinical frameworks that were not designed to address the particular challenges of environmental surveillance. Stakeholders consistently pointed to the need for clearer global guidance, particularly on issues such as informed consent, data-sharing, community engagement and the management of data that may indirectly identify populations. Without a more formalized ethical foundation, programmes are left to navigate difficult questions on a case-by-case basis, and there is uncertainty about how to balance the public health benefits against privacy, autonomy and fairness. It will be essential to move this conversation towards shared ethical standards that are globally recognized and grounded in the realities of WES to ensure that systems are both trusted and sustainable.

4.1.9 Digitalization pathways for WES

The digital tools used for WES are diverse and continue to evolve. Despite this heterogeneity, there are promising opportunities to integrate a dedicated digital module for WES within existing surveillance and data management systems. While workflows for WES remain underdeveloped in many contexts, they are gradually expanding in scope and use across settings. To be effective, such a module should prioritize user personas and task-based interactions to ensure functionality, usability and responsiveness to operational needs.

4.2 Considerations

4.2.1 General considerations

The findings of this landscape analysis point out that WES is at a critical juncture. As interest grows in expanding WES to cover multiple pathogens and align or integrate it with existing, standardized

global and country surveillance models, there is a risk of building complexity atop an unstable foundation. While the ambition to scale up is understandable, and in some contexts necessary, many existing systems face unresolved challenges in data interpretation, governance and integration and its use for decision-making. Without addressing these fundamental gaps, expansion efforts may outpace a system's ability to deliver reliable, trusted and actionable data.

Rather than prioritizing rapid scale up or rigid standardization, efforts should first focus on strengthening the core elements of WES. This includes investing to develop capacities to interpret data from such surveillance, to advance research to make WES easier to implement, to establish durable governance mechanisms and to foster meaningful collaboration across sectors. A one-size-fits-all approach may offer the appearance of coherence, but it risks ignoring the operational realities and institutional constraints that define how WES functions in different contexts.

Policy frameworks should, therefore, be designed to accommodate diversity and different country contexts. Flexibility is key, allowing countries to develop surveillance systems that reflect their own infrastructure, public health priorities and social contracts. Capacity-building must go beyond laboratory training to include institutional development and national ownership. Partnerships with academia and the private sector should continue to drive innovation, but with clearer pathways for sustainability, local stewardship and equitable benefit-sharing. Equally important is the need to embed ethical considerations and community engagement into the early stages of the surveillance process. The collection and use of wastewater data often unfold with limited public visibility, raising concerns around privacy, consent and accountability. These are not peripheral issues: they are central to the legitimacy and long-term sustainability of WES. Governance frameworks must address these issues, ensuring that the benefits of surveillance do not come at the cost of public trust.

It is essential to consider cost-effectiveness in future planning. WES can deliver efficiencies at scale, especially through its low marginal costs and ability for multi-pathogen testing. However, its financial

viability depends on whether the information it provides is reliable, easy to interpret and effectively used to support public health decisions. Additional cost-effectiveness studies are needed in different settings to clarify under which conditions WES delivers added value relative to investment.

In short, the path forward is not to mould WES into a single global template, but to support countries in building strong, context-responsive foundations by starting with descriptions of processes and methods to enhance data reliability, interpretation and comparison. From there, expansion can be both strategic and sustainable, driven by public health value not just technical possibility. The long-term credibility and relevance of WES will depend on systems that are not only capable of collecting data but also of interpreting it accurately, governing it ethically and integrating it meaningfully into the wider landscape of public health surveillance.

4.2.2 Considerations for WHO

The findings of this landscape analysis reflect a clear expectation from stakeholders that WHO has a role to play in advancing WES, which is informed by its historical leadership in environmental surveillance for poliovirus. At the same time, WES, as a multi-pathogen surveillance approach, remains an evolving field, and questions remain regarding the quality and interpretation of its data, as well as its governance and operational integration. WHO's role in WES keeps evolving, as countries and partners continue to assess how WES can best be positioned within broader surveillance systems.

As the global scientific and coordinating authority for public health, WHO's roles in WES are fundamentally to focus on setting norms and standards, provide technical guidance, facilitate international cooperation and support countries to strengthen their surveillance systems. Thus, one of WHO's main responsibilities will be to promote practices that will ensure WES generates robust scientific evidence that is useful for global health governance.

Stakeholders recognize, however, that the current variability in WHO's engagement with WES across regions and departments reflects legitimate differences in regional priorities, capacities and demand from Member States. This is not

unexpected. Yet in the absence of a clear position from WHO, there is a risk that the evolution of WES may be shaped by interests that are not aligned with public health principles. Without guardrails, WES could be repurposed, intentionally or unintentionally, for objectives that extend beyond health and that potentially have consequences for equity, privacy, global health security, global partnerships and community trust in public health surveillance. The proliferation of surveillance models driven by security, political or commercial interests, rather than by transparent public health goals, could undermine the credibility of WES and erode its value as a public health good.

This highlights the importance of WHO acting in a timely manner, not as an implementer but as a leader in developing norms that prioritize meeting countries' needs. To fulfil this role while recognizing the limits of its mandate, current funding circumstances and competing priorities, WHO needs to develop a cross-departmental and cross-regional roadmap that articulates how WES fits within WHO's mission and within the global surveillance architecture. Such a document would help set shared expectations for Member States, donors, technical partners and, potentially, other United Nations agencies. It would clarify that WHO's leadership focuses on supporting countries to develop WES systems that are ethically governed, scientifically robust and fully integrated within broader health surveillance systems.

4.2.3 Considerations for the global public health community and external partners

The global public health community – including international organizations, donors, technical partners and research networks – has an important role in supporting the responsible development and long-term sustainability of WES. This support should be grounded in efforts to reinforce country ownership, strengthen health systems and ensure that WES remains aligned with public health goals rather than emerging as a parallel or donor-dependent system.

Priorities should include fostering financing models that go beyond short-term projects and supporting the development of dedicated budget lines, contingency funding mechanisms and the financial

frameworks needed for countries to sustain WES as part of their broader surveillance infrastructure.

Support for developing harmonized but adaptable laboratory protocols and data standards is equally critical, ensuring that WES outputs are both reliable and comparable, while respecting the need for contextual flexibility.

Investing in decentralized capacity-building efforts remains a central responsibility of this community. Capacity-building must include not only technical laboratory training but also efforts to strengthen workforce capacities in system governance, data interpretation and cross-sector coordination. Identifying or strengthening national lead institutions will help ensure that WES is integrated within existing surveillance structures and that coordination mechanisms are durable and led by countries.

Finally, the global public health community will play a key role in integrating WES into routine public health surveillance by helping countries define how WES fits within their national surveillance strategies. This may include supporting the development of operational pathways for data use, response protocols and decision-making mechanisms that ensure WES contributes meaningfully to public health action rather than operating as an isolated or exploratory tool.

4.2.4 Considerations for Member States

Where WES is determined to be a valuable tool, Member States, national governments and public health authorities all play central roles in enabling its success, by providing policy support and developing dedicated funding models that move WES beyond temporary, project-based structures and into routine public health practice. It is critical to leverage existing laboratory, data and surveillance infrastructure not only to improve efficiency but also to strengthen country ownership and enable nationally driven decisions about priority pathogens and surveillance strategies.

Establishing clear institutional leadership is important. Designating lead agencies or institutions to coordinate WES activities will help ensure operational coherence, foster integration with other

surveillance systems and strengthen governance. Activities to define clear leadership will include clarifying roles across sectors, defining data-sharing protocols and embedding ethical standards that protect privacy, ensure transparency and build public trust. Ultimately, WES should be viewed as one component of a comprehensive, integrated and resilient surveillance system that, first and foremost, will serve national public health goals. Member States should also consider conducting systematic cost-effectiveness evaluations to provide evidence about financial considerations for implementation.

4.2.5 Considerations for those implementing WES

Engaging in WES requires careful consideration of whether, where and how it adds value within a given context. Before initiating or expanding WES, it is critical to assess how it aligns with national priorities, whether it complements existing surveillance systems and what the operational trade-offs may be.

WES is not a one-size-fits-all solution. Its success depends on clearly understanding its purpose, the problem it is meant to solve and the capacity of the system to effectively use the data collected. Before investing in technical platforms or laboratory capacity, the first step should be to avoid duplicating efforts, particularly those of existing surveillance mechanisms, and to conduct a realistic assessment of the benefits and limitations of WES.

- For those initiating WES, its foundation must be built on early and continual engagement with all relevant stakeholders from the community to the national level. The prerequisites of sustainability are to build trust, and to ensure ethical implementation and that the right questions are asked, from who will benefit and how data will be used to how communities will participate in the implementation process. It is essential to learn from previous programmes, including those that have struggled, to avoid repeating mistakes, particularly when technical ambitions are not matched by pathways for governance, coordination or data use.
- For those already implementing a WES programme, attention should shift towards strengthening its operational relevance and

ensuring that it remains aligned with public health needs. Capacity-building should be responsive to local contexts and focus not only on laboratory skills but also on practical problem-solving, operational adaptability, ethical governance and effective cross-sector collaboration. Research agendas must be rooted in the day-to-day challenges of surveillance, particularly in resource-constrained settings, and must remain focused on the quality of data, how data are interpreted, and the fair and effective use of outputs.

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¹ All references were accessed on 13 August 2025.

Annex 1. Methodology

1 Sampling methods and selection criteria

Purposive sampling was used to recruit participants based on two main criteria, namely their involvement with WES and the geographical area where the surveillance was implemented.

First, in terms of a participant's contributions to WES, stakeholders were recruited who had current or past involvement in operational implementation, policy development or research. Experts engaged in broader surveillance activities were also recruited if they had collaborated with WES stakeholders. To capture anticipatory insights, we included individuals involved in planning for or considering a future implementation of WES.

Second, we intentionally worked to ensure wide geographical and income-level representation by including participants from low-, middle-, and high-income countries. We also aimed to target individuals who are involved in WES at various levels, from a global perspective to regional, country-specific and even local levels of implementation. Additionally, we sought those involved in diverse implementation settings, such as urban and rural areas, or institutions working in humanitarian contexts.

Generally, participants were required to have working proficiency in any of four United Nations languages, namely Arabic, English, French or Spanish. When this was not possible, professional interpretation was arranged to facilitate communication.

After the initial communication with prospective participants, people were excluded if they did not have relevant experience or had no foreseeable involvement in WES (e.g. in planning, implementation or collaboration). WHO regional and country teams could join the interviews as observers, but not as study participants.

2 Identifying and selecting participants

Three approaches were used to identify and invite participants for the study. These were:

- Nomination by WHO regional offices of countries and institutions within their jurisdiction that were either implementing or actively planning to implement WES;
- Invitation of experts who had previously worked or were still working with various WHO departments on topics related to WES;
- Snowball sampling to reach other relevant stakeholders, following recommendations from participants who were interviewed.

2.1 Orientation and consultative meetings

We conducted orientation and requested consultative virtual meetings with regional offices to discuss the objectives and scope of the study and obtain recommendations about key stakeholders in their regions. Staff at regional offices assisted the research team in identifying and contacting focal points in countries that were implementing WES. In turn, these focal points identified personnel in their institutions who were actively involved in various aspects of WES implementation.

To ensure geographical representation, each regional office nominated at least three countries for participation. The study team and regional offices agreed to prioritize countries that had already implemented WES projects or embedded it into routine surveillance, and those considered to have advanced plans to implement WES. Additional considerations for nominating countries and projects included ensuring variations in demography and income levels, and assessing demonstrated use cases of WES, surveillance objectives and needs, and health systems capacities. Based on the countries and projects recommended by the regional offices, we liaised with focal points and identified participants from ministries of health, other

ministries and government agencies who could speak to the objectives of the study.

2.2 Selecting subject matter experts

In consultation with other WHO units that are working on different aspects of WES, we obtained a list of subject matter experts from research and academic institutes, national public health technical agencies and partner organizations. Their career profiles were reviewed to ascertain their scope of work and alignment with the scope and objectives of our study.

2.3 Identifying additional participants by snowball sampling

To enhance the richness of perspectives, snowball sampling was used to identify stakeholders who participants recommended as able to share additional insights with the study. Deliberate attempts were made to identify and reach individuals beyond formal WHO networks, especially those who may be less visible with conventional sampling considerations. Further, earlier participants were asked to recommend individuals with critical or sceptical views of WES from whom the study team could obtain different perspectives. This strategy aligned with the study's exploratory and problem-oriented nature, allowing it to surface a broad spectrum of insights, including those that may challenge prevailing narratives.

2.4 Inviting and scheduling participants

After identifying potential participants, individuals and project teams were emailed invitations that contained an abridged version of the interview guides (Annexes 2–5). If they consented to participate, they had the option to choose the topics in the interview guide that they were able to discuss. If they needed additional information for institutional clearance to participate, it was provided. Interviews were then scheduled at the convenience of the participants, taking into consideration their time zone.

3 Data collection

Between 22 October 2024 and 21 February 2025, data were collected using a flexible combination of interviews with individual subject matter experts and WES implementation teams. Interviews with individuals were used to engage those in senior, strategic or specialized roles who required flexibility in terms of the duration and depth of the discussion. This method allowed participants to reflect openly on nuanced or sensitive aspects of implementation, especially in situations in which institutional or political complexities shaped their engagement with WES. The interviews with the implementation teams enabled rich exchanges among participants and helped us generate collective insights, especially around shared institutional challenges and collaborative practices. The interactions allowed participants to react to and build upon one another's experiences, enhancing the scope and depth of insights.

Each session lasted between 60 and 90 minutes and was led by at least two members of the study team. At the beginning of each session, the study's objectives and procedures were explained, participants' questions were addressed, and verbal consent to record the audio of the conversation was obtained. Participants were assured of confidentiality and encouraged to express their views openly.

Problem-centred interviews were conducted using a semistructured guide (Annexes 2–5). These guides allowed for the flexible sequencing of questions to preserve the narrative flow of participants. Participants responded to questions about a range of key topics including:

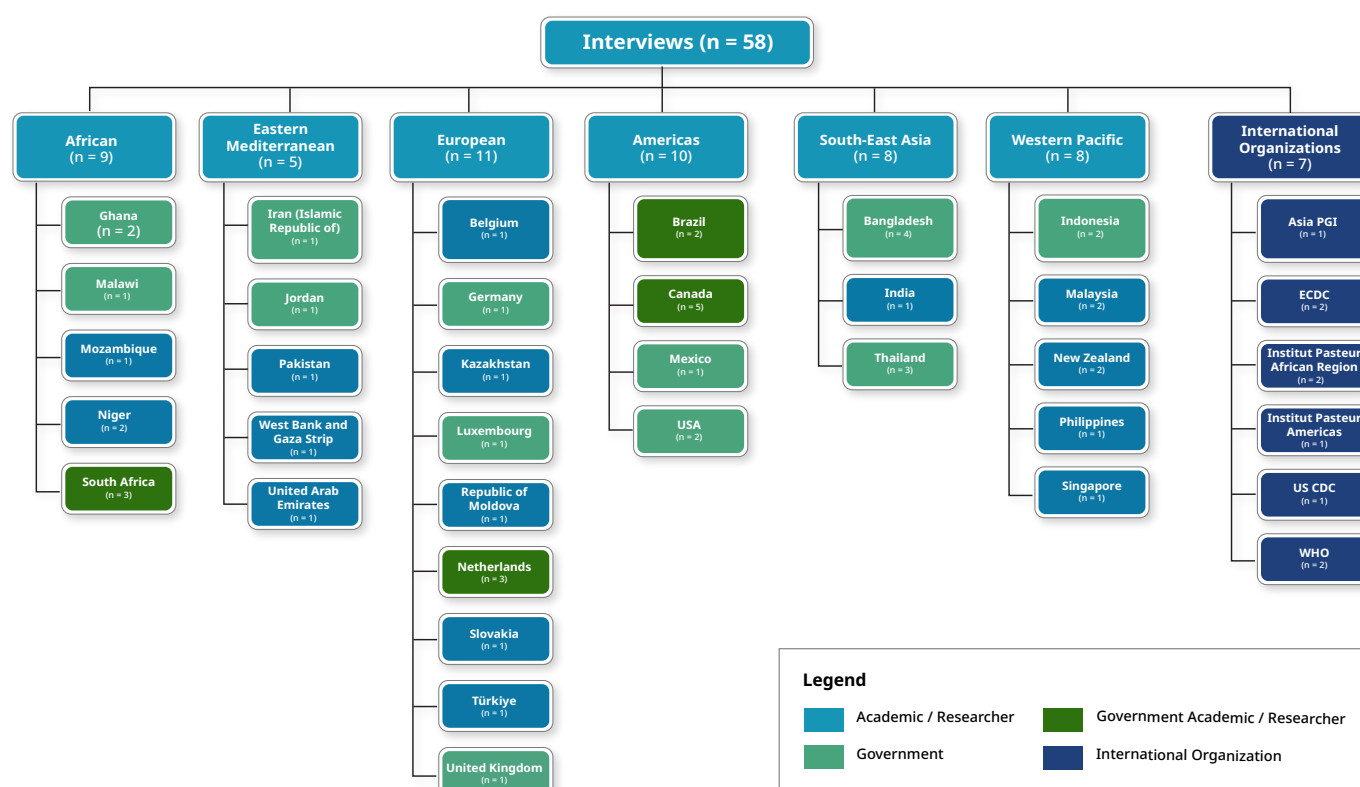
- Implementation challenges, including how WES is integrated into national public health systems;
- Strategies for transitioning WES projects into routine surveillance;
- Enablers, best practices and innovations in conducting WES;
- The perceived role of WHO in supporting the development of WES;

- Ethical considerations;
- The effects of climate change on WES systems;
- Considerations for digitalizing WES workflows.

We transcribed the audio from all sessions verbatim using Microsoft Teams' artificial intelligence, and a combination of manual transcription and automated speech recognition tools. We reviewed and edited the transcripts for accuracy and anonymized them by removing personal and institutional identifiers. Any other parts of an interview that might identify a participant were also removed, such as their specific workplace, geographical location or specific setting

or device. In this report, participants are identified only by their role (e.g. in academia, research, a nongovernmental organization [NGO], government) or country status (low- and middle-income country [LMIC], high-income country [HIC]). Due to constraints of time and workload on the part of both the study team and participants, we did not return transcripts for checking by participants. However, two study supervisors performed random validation of a cross-section of the transcripts by listening to the recordings. In total, we conducted 58 interviews with 127 stakeholders across the six WHO regions (Fig. 1).

Fig. 1. Distribution of participants, by WHO region and stakeholder position for the global landscape analysis of wastewater and environmental surveillance



Asia PGI: Pathogen Genomics Initiative; US CDC: United States Centers for Disease Control and Prevention; ECDC: European Centre for Disease Prevention and Control; WHO: World Health Organization.

4 Data management

Transcripts were stored in a secure, password-protected digital environment accessible only by authorized members of the research team. After transcribing the interviews, we performed data quality checks and cleaning to ensure accuracy and completeness. We used the Track changes features in Microsoft Word during the data cleaning process to ensure transparency and facilitate auditability. A unique alphanumeric identifier was assigned to each transcript, to facilitate secure tracking and auditability across the coding and analysis phases.

Data files were organized into a structured directory system, including folders for raw transcripts and documentation of transcript quality checks. A master file was maintained to track interview dates, participants' roles and participants' WHO region. All participants provided written consent in their acceptance emails, and the emails were retrieved

and stored separately from the transcripts to maintain confidentiality.

The clean transcripts were imported into MAXQDA Analytics Pro (v. 24.9, VERBI, Berlin, Germany) for qualitative data management and analysis. To support stratified analyses, within MAXQDA, each transcript was tagged with descriptive variables, namely WHO region, country, income status of country and the institutional affiliation of the participant.

Consistent versions were maintained throughout the data management process. The codebook, memos, audit trail and project logs were backed up regularly and stored in encrypted cloud-based repositories to ensure data integrity, traceability and compliance with best practices for research data management.

5 Data analysis

Transcripts were deductively coded and thematic analysis of the data was performed.

5.1 Developing a coding system

The analysis was based on an a priori developed coding system and the objectives and scope of study. Drawing from the topics in the interview guide and insights that emerged from the interviews, 11 thematic areas were initially identified. Each thematic area was defined as a parent code, and a corresponding set of subcodes was developed inductively from the transcript data to capture more specific subthemes (Annex 6).

To ensure consistency and transparency, memos were developed for each parent code and code-level memos for each subcode. The code-level memos detailed the definitions and how to apply the codes to identify segments of transcripts with relevant data. This initial coding system, comprising the parent codes and their corresponding subcodes, underwent multiple rounds of review by the study

team. The study team revised the coding system to incorporate previously overlooked themes, eliminate redundancies and improve clarity. Two project supervisors provided further feedback, resulting in a finalized coding framework consisting of 11 parent codes and 66 subcodes (Annex 6). The entire process of developing and validating the coding system was documented for quality assurance purposes.

5.2 Thematic analysis

The study team initially became familiar with the data through the interviews and the data cleaning process. Further, the team read the clean transcripts in full to ensure immersion and contextual understanding.

Using the finalized coding framework, one study team member conducted deductive coding with the support of the AI Assist feature in MAXQDA Analytics Pro (v. 24.9). This feature searched the transcripts, highlighted relevant text segments and suggested subcodes based on the previously defined memos.

For each suggested segment, AI Assist generated explanatory comments about the rationale for the proposed coding.

One member of the research team systematically reviewed the suggested codes, verifying the relevance and completeness of the highlighted segments in accordance with the subcode definitions. Relevant suggestions were either accepted or edited for completeness, while irrelevant ones were discarded.

Subsequently, the same team member performed thematic analysis using the coded segments. For each transcript, all retrieved segments were grouped under their respective subcodes and analysed collectively within MAXQDA. This approach enabled the identification of recurrent themes and patterns within each subcode. The analysis output included numbered references for each coded segment, organized in the order of retrieval to facilitate review and validation of the analysis.

These results were exported into a Microsoft Excel workbook (v. 16.95.1; Microsoft, Redmond, WA, USA). A second study team member then reviewed the thematic outputs, removed the reference numbers and developed concise summaries of the segments for each subcode. These summaries were further compiled under the broader parent codes, forming the basis for a draft analytical report. Two project supervisors performed a blinded review of the first draft of the report for contextual accuracy and coherence. The study team and supervisors discussed the feedback from the review and revised the report. Illustrative verbatim quotes from interviewees were then integrated into the report to substantiate the key findings.

Members of the study team and the project supervisors all have extensive prior experience in public health, surveillance systems and qualitative research, which facilitated building rapport with

participants and informed a nuanced interpretation of the data. Throughout the research process, each team member continually reflected and examined their own assumptions, perspectives that were informed by their work and potential biases (reflexivity). Regular team discussions were held to interrogate emerging interpretations, promote analytical rigor and ensure that diverse and divergent viewpoints within the data were accurately and equitably represented.

6 Ethical considerations

All participants provided informed consent prior to being interviewed after having been fully briefed on the purpose of the study, the voluntary nature of their involvement and their right to withdraw consent at any stage without penalty.

To protect the confidentiality of participants, all interview transcripts were pseudonymized during transcription. Identifiable information was removed or replaced with neutral descriptors to prevent responses from being attributed to specific individuals or organizations.

Data privacy and protection were prioritized throughout the study. All digital data, including the transcripts and analysis files, were securely stored on password-protected servers with access restricted to authorized members of the research team. These measures ensured compliance with relevant data protection regulations and safeguarded the integrity and confidentiality of the research data.

7 Methodological strengths and limitations

7.1 Strengths

First, this qualitative analysis drew on interviews with a diverse set of stakeholders, conducted across 31 countries in all six WHO regions and from six international public health organizations. Thus, it offered a rich and contextually grounded understanding of global WES implementation. The inclusion of participants from varied institutional backgrounds – ranging from public health authorities and laboratory personnel to environmental agencies and international partners – enhanced the representativeness of perspectives and the external validity of the conclusions.

Second, the study adopted comprehensive deductive coding and thematic analysis. These were supported by the AI Assist feature in MAXQDA Analytics Pro (v. 24.9). The supervised application of this feature enhanced the consistency and transparency of the coding process and facilitated the identification of both cross-cutting themes and context-specific nuances.

Third, the study team held regular debriefings and discussions throughout the design, analysis and report-writing processes. This further strengthened the quality, credibility and trustworthiness of findings.

7.2 Limitations

Despite these strengths, some methodological limitations must be acknowledged.

First, while the study included a wide range of countries and stakeholders, the selection of participants was influenced by their availability and willingness to participate, introducing the possibility of selection bias. Stakeholders from regions with limited WES implementation or constrained communication infrastructure may have been underrepresented, potentially skewing the global perspective. To mitigate this bias, the study team

used purposive sampling and snowball sampling to reach participants from less recognized settings and projects to enhance representativeness.

Second, the interviews were primarily conducted in English, with translations provided when participants preferred to speak their official language, namely Arabic, French and Kazakh. Thus, some contexts and meaning may have been lost in translation. A member of the study team was multilingual: fluent in Arabic, English, French and Spanish. He performed data cleaning and validation of all the non-English transcripts to mitigate this risk.

Third, while AI-assisted coding improved analytic efficiency, it may have overlooked subtle contextual meanings or culturally specific expressions that human coders typically detect, especially during multicountry analyses. To mitigate this, each AI-suggested code was reviewed line by line by a data analyst from the study team who has expertise in qualitative methodologies. In some cases, manual coding was used, and AI-assigned segments were either revised or discarded to maintain relevant coded segments for onward thematic analysis.

Nevertheless, the findings should be interpreted with an understanding of these inherent constraints and the exploratory nature of qualitative global landscaping analyses.

Annex 2. Information collection tool T1 for international organizations

This tool was used during the problem-centred interviews. It provides a semistructured guide for the interviewer.

- **Opening question:** Can you briefly describe your role within wastewater and environmental surveillance (WES) implementation? Can you briefly share your objectives, rationale for choosing WES, pathogen or phenomenon under study, decisions, and interventions based on WES and the outcomes of the project/s?
- **Probing questions to include:** Did you envisage upscaling this project to regular surveillance? What was your plan to sustain WES?
- **Enablers/facilitators:** From your perspective, what are the enablers that implementers are benefiting from while implementing WES? (List top three with brief details.)
- **Prompts:** enablers that facilitated the effective implementation of WES, which could be policy/guidelines, governance and coordination mechanisms, trained human resources, infrastructure, funding, data use and dissemination.
- **Challenges during implementation:** From your perspective, what are the challenges implementers are encountering while implementing WES and sustaining it? (List top three with brief details.)
- **Prompts:** knowledge gaps, pathogen prioritization, site selection, wastewater infrastructure, laboratory methods and capacity, standard operating procedures, analytical capabilities, lack of government support, funding.
- **Interventions to transition from project to sustainable programme:** In your experience/opinion, which interventions or support could help facilitate such transitions from a project to regular surveillance?
- **WES and climate change:** Can you briefly describe whether WES may be helpful in the emerging context of climate change and health effects? How? (List top three with brief details.) How could climate change impact WES? (List top three with brief details.) Suggestions to build resilient WES?
- **Ethics:** Do you see any ethical considerations while working with WES implementers?
- **Prompts:** privacy and data protection, community trust, transparency, how such concerns were managed, ethical best practices or gaps to inform future implementation.
- **Role of WHO:** In your view, what role can WHO play in supporting WES implementation and scale up, and embedding it into public health surveillance systems?
- **Identifying in-depth interview candidates:** Can you help us identify other implementations of WES and relevant focal points to approach to ask them to participate in in-depth interviews for a landscape analysis and for gathering information about data flows and end-user requirements?

Annex 3. Information collection tool T2 for implementers (academia/research)

This tool was developed specifically for interviews with academics and researchers. It covers the rationale for wastewater and environmental surveillance (WES), and its objectives, scope, processes and integration into broader public health systems. It explores key dimensions, such as challenges, enablers, lessons learned, ethical considerations and the potential role of WES in addressing emerging issues such as climate change.

- **WES implementation:** Can you describe the WES implementation you are involved in?
 - Rationale
 - Objective of the surveillance
 - Scope: pathogen, drugs, antimicrobial resistance
 - Governance mechanism for the surveillance
 - Funding
 - Process
 - Number of sites, population coverage
 - Stakeholders involved and coordination
 - Sampling type
 - Laboratory processes involved
 - Data management processes: tools, analytics, and usage or triangulation with other surveillance data
 - Outputs: quantitative versus qualitative, and how they are used for decision-making
 - Sharing of outputs
 - How does WES fit into the larger public health surveillance ecosystem in the country? Can you describe it using an example?
 - Is the output from WES used as part of multisource collaborative surveillance and used routinely in risk assessments? Can you give us an example?

- What decisions have you made using WES data? Could you give some examples from your implementation?

- **Challenges:** What challenges (technical and operational) did you face in the various implementation phases:
 - In designing the surveillance, including knowledge gaps, selection of pathogens and sites, periodicity of sample collection, sampling, lack of standards and guidelines;
 - During initial implementation and roll out, including sampling, sample transportation, testing, data analysis and use, feedback mechanisms;
 - In sustaining implementation, such as resource availability, acceptability, usefulness;
 - During expansion/upscaling, such as resource prioritization, policy, lack of standards, guidelines, lack of infrastructure.

In your opinion, what could have been better, or in other words, which solutions/interventions could have facilitated better implementation?

- **Enablers:** From your experience, can you tell us about the minimal prerequisites for initiating and implementing WES (e.g. laboratory network and capacity, guidelines, standard operating procedures, sewage network, legal policy)?
 - What role can WHO play in this regard: in your country and as a common good that can be used for other countries?
 - Some of the research projects focusing on WES, although successful, often do not convert to use as regular surveillance mechanisms; what are your thoughts on this? What could be the reasons for this in your experience?

- **Best practices and lessons learned:** In your opinion, what are the best practices from your WES implementation that other countries could potentially learn from and emulate?
 - From your experience, what do you think about the use of WES in public health surveillance in the future?
- **Support:** Did you receive any support for your implementation from external agencies? What was the support, and which external agency was involved?
 - Which areas of WES implementation need more attention, and where should more research be focused (e.g. modelling, pathogen-specific shedding patterns, duration of shedding, the rate of decay in wastewater, detection limits in wastewater)?
 - Which agencies/partners can help in this regard?
- **Climate change**
 - Do you think WES can play a role in the surveillance of health effects/risks due to climate change? If yes, can you briefly describe how?
- In your WES implementation, have you considered the effects of climate change (e.g. floods, storms, droughts, rising groundwater levels) on sewer infrastructure and the resulting impacts on WES? Have you taken any mitigation measures? Can you briefly describe them?
- **Ethics**
 - Were there any ethical considerations or dilemmas during the planning or implementation of the WES project?
 - How were issues such as privacy, data confidentiality, community engagement or informed consent addressed?
 - Were any concerns raised by stakeholders (e.g. communities, government, partners) regarding ethical aspects of WES?
 - From your perspective, how could ethical considerations be better integrated into WES planning and implementation in the future?

Annex 4. Information collection tool T3 for government officials

This tool was developed specifically for interviews with government officials to capture their experiences with and perspectives on the implementation of wastewater and environmental surveillance (WES). It covers the rationale, scope, processes, challenges, decision-making, lessons learned and ethical considerations, as well as the role of WHO and partners in supporting the future directions of WES.

- **WES implementation:** Can you describe the WES implementation you are involved in?

- Rationale
- Objective of the surveillance
- Scope: pathogen, drugs, antimicrobial resistance
- Governance mechanism for the surveillance
- Process
- Number of sites, population coverage
- Stakeholders involved and coordination
- Data management processes: tools, analytics and usage, along with other surveillance data
- Outputs: quantitative versus qualitative, and how they are used for decision-making
- Sharing of outputs

- **Decision-making:** How does WES fit into the larger public health surveillance ecosystem in the country?

- Can you describe this using an example?
- Is the output from WES used as part of multisource collaborative surveillance and used routinely in risk assessments? Can you give an example?
- What decisions have you made using data from WES? Could you give some examples from your implementation?

- **Challenges:** What challenges (technical

and operational) did you face in the various implementation phases:

- In designing the surveillance, including knowledge gaps, selection of pathogens and sites, periodicity of sample collection, sampling, lack of standards and guidelines;
- During initial implementation and roll out, including sampling, sample transportation, testing, data analysis and use, feedback mechanisms;
- In sustaining implementation, such as resource availability, acceptability, usefulness;
- During expansion/upscaling, such as resource prioritization, policy, lack of standards, guidelines, lack of infrastructure.

- **Best practices and lessons learned**

- In your opinion, what could have been better, or in other words, which solutions/interventions could have facilitated better implementation?
- From your experience, can you tell us about the minimal prerequisites for initiating and implementing WES (e.g. laboratory network and capacity, sewage network, legal policy)?
- In your opinion, what are the best practices from your WES implementation that other countries could potentially learn from and emulate?

- **Role of WHO and other organizations**

- What roles can WHO play in your country and in acting as a common good for other countries?
- Did you receive any support for your implementation from external agencies? What was the support, and which external agency was involved?

- **Next steps:** Which areas of WES implementation need more attention, and where should more research be focused (e.g. modelling, pathogen-specific shedding patterns, duration of shedding, the rate of decay in wastewater, detection limits in wastewater)?
 - From your experience, what do you think about the use of WES in public health surveillance in the future?
 - Do you think your country is progressing in this direction? If not, what needs to be done, and how can WHO help?

Ethics

- Were there any ethical considerations or dilemmas during the planning or implementation of the WES project?
- How were issues such as privacy, data confidentiality, community engagement or informed consent addressed?
- Were any concerns raised by stakeholders (e.g. communities, government, partners) regarding ethical aspects of WES?
- From your perspective, how could ethical considerations be better integrated into WES planning and implementation in the future?

Annex 5. Information collection tool T4 for in-depth interviews to guide end-user requirements for a digital module

This tool was used to understand which features of a digital module would be most valuable to end-users engaged in wastewater and environmental surveillance (WES). It explores current data collection workflows, essential data fields, quality and validation needs, integration and interoperability requirements, and recommendations for future digital tool development.

- **Current data collection practices and workflow:** Which types of data are currently collected for WES in your department?

Can you describe the workflow for WES in terms of:

- Coverage of surveillance – diseases and phenomena (e.g. antimicrobial resistance);
- Data collection;
- Sources of samples;
- Methods of sample collection;
- Frequency of sampling;
- Packaging and labelling methods (e.g. use of barcodes or manual labelling);
- Lab procedure for receiving and assessing samples;
- Data analysis;
- Methods of reporting;
- Frequency of reporting results;
- Visualization (e.g. dashboards).
- **Data collection fields in a digital WES tool**
 - Which specific data fields would you consider essential for a digital tool for WES? Follow up: Why are these fields critical to your operations?

- How should the data be structured in the tool? Follow up: Should there be standardized templates or customizable fields?
- Are there specific environmental parameters or indicators that should be prioritized in the tool? Follow up: How would you prioritize these fields in terms of importance?

- **Data quality and validation**

- Which quality control measures should be implemented in the digital tool for data collection? Follow up: How should the tool handle data validation, error checking and anomaly detection?
- How important is it for the tool to support real-time data validation and correction? Follow up: What are the potential challenges in implementing this feature?
- Which methods do you currently use to ensure the accuracy and reliability of the data collected? Follow up: How should the digital tool integrate with or enhance these methods?

- **Integration and interoperability**

- How should the digital tool integrate with other systems or databases used by your department? Follow up: Are there specific systems or databases that the tool must be compatible with?
- Which data export/import functionalities are necessary for the tool? Follow up: How should the tool support data-sharing with external partners or stakeholders?

- How should the tool handle data standardization and interoperability with international or national standards?
- Are there specific standards that the tool must adhere to?
- **Future needs and recommendations**
 - If you could improve one aspect of data collection for WES, what would it be? Follow up: How should the digital tool address this issue?
 - Do you have any additional recommendations or comments regarding the development of this digital tool?

Annex 6. Qualitative coding system for wastewater and environmental surveillance

Table A5.1 presents the qualitative coding system used in this analysis. It consists of 11 parent codes, which are further divided into 66 subcodes. Each parent code and subcode is described by accompanying memos.

Table A5.1. Qualitative coding system

Parent code	Parent code memo	Subcode	Subcode memo
Current practices	Descriptions of current methodologies, protocols, and strategies for WES; any mention of WES sampling, data collection, testing procedures and real-world applications of WES data in public health decision-making	Site selection	This refers to code data that state the no. of sampling sites and factors considered in creating, maintaining and closing down sites.
		Geographical coverage of implementation	Identify descriptions about the geographical scale of implementation, such as whether they are pilots, or at the subnational or national level.
		Targets covered	Identify the names of infectious agents, pathogens or diseases that countries detect using WES. Identify the use of WES to track antimicrobial resistance.
		Sampling methods	These code statements describe where, how and how often samples are collected.
		Data collection	Identify mentions about how WES data are collected and stored.

Parent code	Parent code memo	Subcode	Subcode memo
		Analysis and reporting	Identify references to how WES results are recorded, processed and shared.
		Decision-making	Capture examples of how data have been used in real-world public health decision-making at the local, national or global level.
		Stakeholders involved in implementation	Identify national institutions, national agencies, laboratories, private sector or international collaborators in WES implementation.
		Data-sharing	Code any segment that addresses challenges, practices or strategies related to the exchange of, access to or governance of WES data across institutions, sectors or jurisdictions.
Best practices identified during implementation	Identification of examples of strategies or approaches considered effective in implementing WES; should be presented as successful models or replicable lessons learned, including innovations that have worked well	Standardized protocols	Identify mentions of standard operating procedures or quality control systems.
		Multisectoral collaboration	Identify examples of joint efforts undertaken across sectors or institutions.
		Timely data use	This refers to code descriptions about how WES data are used quickly to inform action.
		Capacity-building	Highlight mentions of training, skills transfer or institutional learning.

Parent code	Parent code memo	Subcode	Subcode memo
Challenges in implementation	Descriptions of obstacles or barriers to implementing WES; may include infrastructure gaps, lack of funding, personnel shortages, coordination problems or regulatory issues	Technical	Identify limitations in technical requirements, such as laboratories and equipment.
		Financial	Identify statements about inadequate or unstable funding.
		Infrastructure	Code statements referring to physical and developmental limitations in city planning, such as the availability and coverage of sewer systems.
		Logistics	Identify mentions of logistical limitations in sample collection, transportation, storage, processing, analysis and reporting.
		Gaps in knowledge about and interpretation of WES data	Identify any segments in which uncertainties are expressed about pathogen-shedding rates, environmental persistence, signal-to-case translation or the interpretation of WES data and models.
		Workforce capacity	Identify mentions of staffing gaps, lack of expertise or training needs.

Parent code	Parent code memo	Subcode	Subcode memo
Enablers of implementation	Statements that describe supportive factors enabling successful WES implementation; may include political will, funding, skilled personnel, community buy-in or leveraging existing systems; look for positive drivers or facilitators	Climate change	Identify connections made between climate change and WES relevance or performance (e.g. content on climate-induced risks, environmental shifts affecting pathogens, sample quality or the need for climate-resilient surveillance systems).
		Governance and policy	Code segments mentioning the lack of national guidance, legal frameworks or coordination.
		Political support	Identify evidence of government support, political will or leadership.
		Funding	Find mentions of donors, development partners or external assistance.
		Technical	Identify the availability of technologies that are used in WES.
		Existing systems	Identify cases in which other systems are used to support or facilitate WES.
		Community acceptance	Identify direct statements or inferences that communities support, understand or trust WES activities.

Parent code	Parent code memo	Subcode	Subcode memo
		Workforce capacity	Identify statements about the availability of adequate numbers of staff, adequate expertise or support for training for continual improvement.
Sustainability and resilience factors	Discussions about ensuring the long-term viability and adaptability of WES programmes; include statements about stable financing, institutional embedding, the development of a skilled workforce, and robust technologies that can withstand future challenges	Funding models	Identify mentions of budget strategies, funding transitions or cost planning.
		Country ownership	Identify content indicating national leadership of and responsibility for WES implementation. This subcode includes information about policy-setting, allocating domestic funding and managing operations with limited reliance on external partners.
		Leveraging of existing systems	Identify cases in which WES activities utilize pre-existing public health, laboratory or surveillance infrastructures. Look for mentions of resource-sharing, integration with other platforms or gains in efficiency from using what already exists.
		Integration with public health surveillance	Capture references to aligning WES with existing national disease surveillance systems. Look for information about interoperability, data-sharing, using WES data in routine reporting, and joint analyses with other health surveillance programmes.

Parent code	Parent code memo	Subcode	Subcode memo
		Prioritization of pathogens	Identify how decisions are made about which pathogens to monitor through WES. Include references to high-impact diseases, emerging threats, technical feasibility, and drivers of policy or funding.
Role of WHO	Description of any views about WHO's involvement in WES, such as technical support, policy guidance, coordination, advocacy or funding mobilization, including both praise and critique of WHO's role	Technical guidance	Capture mentions of WHO guidelines, toolkits or expert advice.
		Capacity-building	Identify training and support activities attributed to WHO.
		Coordination	Identify the role of WHO in facilitating cross-country or cross-sector collaboration.
		Advocacy	Note references to WHO's efforts to promote WES or mobilize resources.
		Critique of WHO's role	Capture dissatisfactions and unmet expectations of stakeholders about the role of WHO in WES.

Parent code	Parent code memo	Subcode	Subcode memo
Roles of other stakeholders	Description of involvement of non-WHO stakeholders, such as national governments, NGOs, donors, academic institutions or the private sector (e.g. roles in funding, implementation, policy support or innovation)	Government ministries	Code mentions of national or subnational government involvement.
		Academic institutions	Code instances of universities or research bodies supporting WES.
		NGOs	Capture mentions of non-state actors contributing to WES.
		Private sector	Identify the involvement of labs, contractors or technology vendors.
		International organizations	Capture the involvement of international organizations.
		Donors	Capture mentions of support from donors for the implementation of WES.
Ethics	Identification of references to ethical issues in WES, including privacy, informed consent, equity and the fair use of data (e.g. concerns about how data are collected, shared and interpreted, especially as they affect vulnerable populations)	NA	NA

Parent code	Parent code memo	Subcode	Subcode memo
Added benefits	Discussions about how WES could evolve or be integrated into broader health initiatives, including potential expansions in geographical and pathogen coverage	Early warning and detection	Identify projections or suggestions of WES enabling early detection, including for outbreak investigation.
		Trend monitoring	Identify statements about future uses of WES to monitor trends in diseases or risks, or outbreaks.
		One Health integration	Code references linking WES to human–animal–environment health.
		Noninvasive	Capture mentions of WES as a noninvasive surveillance mechanism compared with traditional clinical surveillance.
		Cost-effective	Capture mentions of the cost-effectiveness of WES for certain pathogens in certain settings compared with traditional surveillance.
		Complement routine surveillance	Capture mentions of WES being useful when clinical surveillance is poor or not present.
		Support targeted countermeasures	Capture mentions of WES being helpful to focus in on a specific pathogen in a specific geographical area to guide and support targeted response measures.
		Recurrent planned mass gatherings	Capture mentions of the use or suitability of WES for planned mass events, such as the Hajj or the Olympics.

Parent code	Parent code memo	Subcode	Subcode memo
		Points of entry	Capture mentions of the role or use of WES at points of entry, such as airports.
		Refugee camps	Capture mentions of the use or suitability of WES in refugee camps.
		Pandemic preparedness	Capture discussions about the contributions of WES to pandemic preparedness.
		Humanitarian situations	Capture discussions about the suitability or use of WES in humanitarian settings, such as during wars or times of civil unrest, or after an earthquake or tsunami.
Recommendations	Identification of clear suggestions for improving WES systems; may relate to technical enhancements, policy changes, funding mechanisms, stakeholder collaboration or scaling strategies; should have an emphasis on forward-looking, actionable guidance	Policy changes	Capture proposed regulatory or legislative shifts.
		Funding models	Capture suggested approaches for securing long-term financing.
		Technical improvements	Identify suggestions for better tools, tests or methods.
		Workforce capacity-building	Identify proposed strategies for workforce training and retention in national health systems.
		Stakeholder coordination	Identify calls for improved collaboration or communication.

Parent code	Parent code memo	Subcode	Subcode memo
Examples of next steps in implementation	Identification of discussion points about planned or proposed future actions for WES expansion or improvement (e.g. upcoming activities, pilot programmes, strategic roadmaps, or directions for research and innovations)	Scaling up	Capture examples of future plans for geographical or programmatic expansion.
		Scaling down	Capture examples of future plans for geographical reduction or programmatic reduction or closure.
		Institutionalization	Identify examples of intentions to make WES part of permanent systems.
		Capacity-building	Identify examples of plans for training or skill development.
		Research and innovation	Identify examples of plans to conduct further research or adopt new technologies or approaches.

NA: not applicable; NGO: nongovernmental organization; WES: wastewater and environmental surveillance; WHO: World Health Organization.

Annex 7. Minimum set of data fields for a digital module for wastewater and environmental surveillance

Component of workflow	Data field	Description	Format of data field	Possible enumerations	Method of field validation	Rationale
Sample site location/ID	Sample site ID or code	Unique identifier for site	Text	Alphanumeric	Cross-check with predefined list or registry	Essential for tracking
	Name	Name of the sampling site	Text	String ^a	Manual entry	Used in reports
	Country	Country where site is located	Text	Fixed list	Drop-down menu	Regional classification
	Region	Regional classification	Text	Fixed list	Drop-down menu	Used for aggregation
	District	District name	Text	Fixed list	Drop-down menu	Administrative classification
	Community	Community name	Text	String	Manual entry	Local classification
	GPS latitude	Latitude coordinate	Float ^b	Numeric	Range validation	Geolocation data
	GPS longitude	Longitude coordinate	Float	Numeric	Range validation	Geolocation data
	Collection site	Specific source of sample	Text	String	Manual entry	Location context
	Collector name or ID	Name or ID of person collecting sample	Text	String	Manual entry	Quality assurance measure

Component of workflow	Data field	Description	Format of data field	Possible enumerations	Method of field validation	Rationale
Sampling and transportation	Type of sample	Type of wastewater or environmental sample collected	Text	Categorical list	Drop-down menu	Basis for analysis
	Collection time	Date and time sample was collected	Timestamp	Four-digit year-month-day and two-digit hour:minute	Autovalidation for format	Must be within defined sampling window
	Volume of sample	Quantity of sample in mL	Numeric	Numeric	Range validation	To assess adequacy
	Transportation method	Method used for transport	Text	Categorical list	Drop-down menu	To confirm temperature-sensitive transport
	Time to lab	Time taken for transport	Two-digit hour:minute	Numeric	Range validation	Cold chain management
	Condition upon arrival	Sample integrity on arrival	Text	Categorical list	Manual verification	Essential for data validity
Environmental data or parameters	Weather conditions	Conditions at time of sampling	Text	Categorical list	Manual entry	To assess external influences
	Water flow rate	Rate of water flow	Numeric	Float	Range validation	Influences concentration levels
	pH level	Acidity of water	Numeric	Float	Range validation	Lab-reported measure
	Temperature of water	Date and time of analysis	Four-digit year-month-day and two-digit hour:minute	Date picker	System timestamp	Quality control

Component of workflow	Data field	Description	Format of data field	Possible enumerations	Method of field validation	Rationale
Laboratory processing and analysis	Lab technician ID	Unique ID of technician	Text	Alphanumeric	Predefined list	Traceability measure
	Analytical methods used	Testing methods used	Text	Categorical list	Drop-down menu	Standardized methodology
	Contaminants detected	Suspended or dissolved solids	Text	Categorical list	Drop-down menu	Surveillance target
	Concentration levels	Levels of contaminants	Numeric	Float	Range validation	Quantification measure
	Quality control measures	Measures for validation	Text	Categorical list	Drop-down menu	Standard procedures
Visualization and reporting	Graphs generated	Types of visualizations	Text	Categorical list	Drop-down menu	Public engagement
	Report generation date	Date of report	Four-digit year-month-day	Date picker	System timestamp	Compliance requirement
	Report author ID	Author identifier	Text	Alphanumeric	Predefined list	Accountability measure
Compliance and regulatory data	Regulatory compliance checks	Adherence to standards	Text	Predefined regulations	Audit log	Accountability measure
	Data-sharing and use	Guidelines about who has access to data and how it can be used	Text	Policy reference	Manual review	Accountability measure

GPS: global positioning system; ID: identification.

^a A string is a data type used to represent textual data, which may include letters, numbers, spaces and special characters.

^b A float (short for floating-point number) is a data type used to represent positive or negative numbers that have decimal points.

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