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Establishment of local wastewater-based surveillance programmes in response to the spread and infection of COVID-19 – case studies from South Africa, the Netherlands, Turkey and England

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ABSTRACT

The COVID-19 pandemic has resulted in over 340 million infection cases (as of 21 January 2022) and more than 5.57 million deaths globally. In reaction, science, technology and innovation communities across the globe have organised themselves to contribute to national responses to COVID-19 disease. A significant contribution has been from the establishment of wastewater-based epidemiological (WBE) surveillance interventions and programmes for monitoring the spread of COVID-19 in at least 55 countries. Here, we examine and share experiences and lessons learnt in establishing such surveillance programmes. We use case studies to highlight testing methods and logistics considerations associated in scaling the implementing of such programmes in South Africa, the Netherlands, Turkey and England. The four countries were selected to represent different regions of the world and the perspective based on the considerable progress made in establishing and implementing their national WBE programmes. The selected countries also represent different climatic zones, economies, and development stages, which influence the implementation of national programmes of this nature and magnitude. In addition, the four countries' programmes offer good experiences and lessons learnt since they are systematic, and cover extensive areas, disseminate knowledge locally and internationally and partnered with authorities (government). The programmes also strengthened working relations and partnerships between and among local and global organisations. This paper shares these experiences and lessons to encourage others in the water and public health sectors on the benefits and value of WBE in tackling SARS-CoV-2 and related future circumstances.

Key words: COVID-19, public health surveillance, SARS-CoV-2, sewage surveillance, wastewater-based epidemiology, wastewater surveillance

HIGHLIGHTS

- Designing and refining methodologies, epidemiological tools and indicators.
- Influencing public health decision-making through research data.
- Experiences on programme design and methodology for WBE surveillance.
- Partnerships strengthening communication and knowledge dissemination.
- Capacity building activities among the science communities, local authorities, industry nationally and internationally.

INTRODUCTION

The COVID-19 pandemic has resulted in at least 340 million infection cases (as of 21 January 2022) and more than 5.57 million deaths globally. The SARS-CoV-2 virus is the newest of the family of coronaviruses associated with human infections that are grouped into the beta-CoV genus, with 79% genetic similarity to SARS-CoV-1 (Pal *et al.* 2020). The outbreak of SARS-CoV-2 was declared a Public Health Emergency of International Concern on 30 January 2020. On 11 February 2020, the World Health Organization (WHO) announced a name for the new coronavirus disease: COVID-19. One month later, the WHO upgraded the status of this coronavirus outbreak from an epidemic to a pandemic.

The emergence of several SARS-CoV-2 variants has become a significant challenge for COVID-19-related policies and vaccination implementation in most countries. In this context, the need to design new and refine existing epidemiological tools, including the use of wastewater-based epidemiology (WBE) to inform decision-making, has increased in many parts of the world. Surveillance programmes have since been set up to monitor the spread of COVID-19 in at least 58 countries (https://ucmerced.maps.arcgis.com/).

The concept of screening municipal wastewater and environmental waters as an epidemiological tool is not new. This approach of using markers of infection has, for instance, been used to help inform broader infectious disease epidemiological surveillance and mitigation efforts such as the Global Polio Eradication Initiative (Hovi *et al.* 2012; Humayun *et al.* 2014). Environmental surveillance has also been used and recommended for the detection of other infections such as typhoid (WHO 2018), hepatitis A and norovirus outbreaks (Hellmér *et al.* 2014), and for antimicrobial resistance (Hendriksen *et al.* 2019). Modelling techniques were used to assist both the design and interpretation of these efforts (Wang *et al.* 2020). WBE is also commonly used to monitor the use of illicit drugs and various chemical contaminants that may impact human health (Choi *et al.* 2018).

Studies have shown the value of WBE surveillance programmes in tracing and monitoring changes in the prevalence of infections in urban populations. This includes, for example, COVID-19 containment on a college campus via wastewater-based epidemiology, targeted clinical testing and an intervention (Corchis-Scott *et al.* 2021). In the Netherlands, test buses were deployed to an area of undertesting (Anon 2022) while in February 2021 in New Zealand, case data was coupled with wastewater data to decide whether to extend a lockdown after three positive cases were detected (Sharara *et al.* 2021). Negative results from wastewater PCR testing at the municipal level allowed government officials to rule out community spread of infections and defined it rather as a contained and traceable cluster of individuals (Sharara *et al.* 2021).

The presence of SARS-CoV-2 in wastewater treatment plant (WWTP) influent, and within the sewer network, can help determine the presence of infection in a community. This is because the detection of SARS-CoV-2 genetic material in wastewater is indicative of the number of COVID-19 cases (dependent on the testing levels of that community) and thus can present a valuable early indicator for local hospitalisations, viral outbreaks or COVID-19 cases (Larsen & Wigginton 2020; Galani *et al.* 2022). This information can be used as an epidemiological indicator even in areas where community testing is not possible, for instance in low-income environments where resources are limited.

WBE surveillance during the pandemic

The objective of this paper is to outline some of the complex conditions under which four countries, namely South Africa, the Netherlands, Turkey and England, found unique ways to navigate their individual paths towards the implementation of WBE surveillance for the tracking of SARS-CoV-2. These methods included the formation of strategic networks and partnerships, the coordination of WBE surveillance efforts at the national and catchment level, the prioritising of actions and resources for tracking SARS-CoV-2, knowledge dissemination and purposeful communication with stakeholders, capacity building, and data collection and analysis. The paper also considers how the data generated were used to inform public health decision-making and ensure future scientific and policy impact.

This section of the paper outlines some of the methods and structures used to establish and coordinate such surveillance programmes, as well as the objectives and strategic intent that informed the efforts. Information was gathered by collecting institutions' own experiences in undertaking WBE surveillance (particularly in the Netherlands, Turkey and South Africa); through discussion groups that shared information on the implementation and challenges of WBE surveillance; and through personal communication with particularly policy- and decision-makers (particularly for the England case study). Due to the qualitative nature of the findings a synthesis as opposed to analysis was undertaken. A concise overview of the implementation of WBE surveillance programmes for SARS-CoV-2 in the studied countries is presented in Table 1.

Table 1 | Overview of implementation of WBE monitoring programmes for SARS-CoV-2 in South Africa, The Netherlands, Turkey and England

	South Africa	The Netherlands	Turkey	England
Programme design, including methodology	• Initial aim: To monitor local and national spread of SARS-CoV-2 in provincial hotspot areas • Evolved into early warning system with pilots in cities and hotspot areas i.e., 38 Wastewater Treatment Plants (WWTP) sites and 21 non-sewered sites) • Focus on sewered and non-sewered communities • Multidisciplinary networks and partnerships, with a leverage model to complement other national surveillance efforts • Three-phased approach to implementation (proof of concept, pilot phase and nationwide rollout) • Variant detection included	• Initial aim: To monitor local and national spread of SARS-CoV-2 and develop methodology for detection of the virus in WWTPs in 6 cities and an airport • Methodology developed, applied and published at early stage of the pandemic • Evolved into a high-resolution analysis of the surveillance pyramid in Rotterdam, alongside a national rollout at all WWTPs in the country • Only sewered systems • Multidisciplinary networks and partnerships implemented to support knowledge exchange and support within the European Union and globally • Variant detection included in the Rotterdam study	• Initial aim: To monitor SARS-CoV-2 distribution nationally • Evolved into early warning system for government, providing routine scanning of 7 geographical regions of Turkey, 21 pilot cities and Istanbul • Focus on sewered systems • Functional interdisciplinary project through involvement of various partners, central governmental and local governmental authorities, governmental entities, and state universities • Systemic methodology, incl. 3 major steps: Planning, Execution and Reporting via governmental dashboards (https://covid19.tarimorman.gov.tr) of several pilots leading to the nationwide surveillance phase • Variant detection included	• Initial aim: To monitor SARS-CoV-2through routine collection and analysis of wastewater samples for SARS-CoV-2 RNA concentrations from WWTPs, in-network sites and near-to-source at critical infrastructure • Evolved into national programme routinely reporting on the detection of variants, providing a prevalence indicator, and case estimates, to inform local response and national strategy • Environmental Monitoring for Health Protection programme (EMHP) monitors SARS-CoV-2 RNA levels in wastewater – covers 70% of the population and major cities • Focus on sewered systems • Pilots focused on determining if WBE could provide a national and regional prevalence indicator and be used effectively to provide local public health insight • In December 2020, EMHP initiated a successful pilot study on the use of whole-genome sequencing to detect SARS-CoV-2 variants in wastewater • Routine reports on the detection of variants in samples from all monitored WWTPs and in-network sites
Programme coordination	• Led by government entities Water Research Commission (WRC), the National Institute of Communicable Diseases (NICD) in partnership with the South African Medical Research Council (SAMRC) • Collaborative engagements with river action groups, community	• RIVM mandated by Ministry of Public Health to start national monitoring program to all WWTPs in The Netherlands. • KWR initiated the programme, also involved experts from Erasmus Medical Centre, Municipal Health Services (GGD) Rotterdam-Rijnmond, the National Institute of Public Health and the Environment	• Led by the Ministry of Agriculture and Forestry and coordinated by the Turkish Water Institute (SUEN)	• Led by Joint Biosecurity Centre within the Department of Health and Social Care (DHSC) now part of the United Kingdom Health Security Agency (UKHSA) and the Department for Environment, Food & Rural Affairs (Defra), the Environment Agency, inputs, and strong

(*Continued.*)

Table 1 | Continued

	South Africa	The Netherlands	Turkey	England
	leaders, universities and research facilitators for monitoring of non-sewered environments	(RIVM, epidemiology), Partners4UrbanWater, Royal-Haskoning DHV (engineering consultancy), Foundation for Applied Water Research, local water authorities (Hollandse Delta, Hoogheemraadschap van Delfland, Hoogheemraadschap van Schieland en de Krimpenerwaard) and KWR		collaboration with universities and academic partners • Multidisciplinary working groups set up in each region
Networks and partnerships (local and international)	• SACCESS network established on a national level • Strategic partnerships were strengthened (including those with policymakers) • Technical partnerships strengthened • Work closely with GWRC • Knowledge-sharing and learning partnerships strengthened (in the co-development of joint knowledge products with NICD)	• KWR shared findings with Dutch water boards, municipalities and international partners and networks • Knowledge-sharing and learning partnerships strengthened through strategic initiatives such as WHO, IWA, WRF, the European Joint Research Centre and EU vs Virus Setting-up and chairing webinar series on sewage surveillance with the Global Water Research Coalition • Strategic partnerships were strengthened (including those with policymakers) • Technical partnerships strengthened (including those with research, laboratory and municipality networks) with Morocco, Kenya, South Africa and Peru • Working with PATH, Michigan State University and UCMerced on W-SPHERE, a global data center for SARS-CoV-2 in wastewater as part of the Global Water Pathogen Project	• Joint venture with China to build a surveillance system using sewage sludge monitoring from a community health perspective • Thematic group for the 9th World Water Forum to provide a platform for knowledge-sharing	• Partnered approach with public health teams at the local authority levels. Results communicated via weekly reporting • National policy and incident response • Technical and research networks across sectors; focusing on sampling, laboratory methods, analysis, epidemiology, and genomics • Inputs into supra-national data sharing repositories to aid international effort
Communication and knowledge dissemination	• Webinars: Targeted at science community local and international (workshops, dialogues, meetings) • Broadcast (TV and Radio), Print media; and Online news: Targeted at public (expert interviews, press releases, factsheets, radio content for local communities) • Website: Dedicated programme pages	• Webinars: Targeted at technical audiences, policy-makers, NGOs, etc. (knowledge sharing dialogues, strategic meetings) • Broadcast Media (TV, Radio, Podcasts): Targeted at the public • Website and dedicated webpage: Targeted at internal and external stakeholders and mainly to respond to public concerns. (News items, project information)	• Webinars: Targeted at international stakeholders, partners and NGOs • Broadcast (TV), Print Media: Targeted at public (non-scientific TV speeches) • Dashboard to share information and data with the general public by the Ministry of Agriculture and Forestry website (https://covid19.	• Seminar presentations and webinars targeted at government, academic and international audiences • Direct communication: Targeted at local health protection teams (insights and data via operational dashboards) • Weekly reporting to the UK Secretary of State for Health and Social Care and the UK Prime Minister

(*Continued.*)

Table 1 | Continued

	South Africa	The Netherlands	Turkey	England
	targeted at internal and external stakeholders • Direct communication: Targeted at municipal authorities, policy and decision-makers • Social media: Targeted at public and WRC social media community • Dashboard to share information and data with the general public: https://www.nicd.ac.za/diseases-a-z-index/disease-index-covid-19/surveillance-reports/weekly-reports/wastewater-based-epidemiology-for-sars-cov-2-in-south-africa/	• Direct communication: Targeted at health authorities and the national Outbreak Management Team, scientists and water authorities • Targeted, strategic communications (best practices guide for communicating science during a public health crisis) • Social media: Targeted at public and KWR and Watershare social media community (LinkedIn, Twitter) • Dashboards, sampling information and methodologies shared, scientific papers published • Dashboard to share information and data with the general public: Dutch sewage surveillance use case (arcgis.com)	tarimorman.gov.tr) (Dashboards, sampling information and scientific papers) • Direct communication: Targeted at local authorities • Social media: Targeted local and international stakeholders (Twitter, YouTube and LinkedIn) • Dashboard to share information and data with the general public	• Direct communication: Targeted at key stakeholders (weekly reports) • Dashboard to share information and data with the general public: Monthly data is published on the government web page 'Monthly statistics for the Environmental Monitoring for Health Protection (EMHP) wastewater program (England) - GOV.UK (www.gov.uk)' • Publications in peer reviewed journals, and Government public communication forums • Engagement via various media channels
Capacity-building activities	• SACCESS network established (network partners collaborated to standardise the methodology and sampling methods now used in surveillance efforts)	• KWR involved in several international capacity-building projects to develop wastewater testing capacities, design regional and national monitoring programmes, and develop tools for reporting and data sharing • Published best practice guidelines to limit misinformation and enhance knowledge dissemination • Supported global community by setting up the global data centre W-SPHERE (see above) and sharing methodologies and lessons learned via Watershare	• COVID-19 Thematic group for World Water Forum March 2022: COVID-19 platform for all COVID-19 groups (global) for the development of capacity building activities for low- and middle-income countries	• Local and national public health teams supported with wastewater data • Secondments, mentorship, and training to post-graduate scientists • Stimulation of UK water industry, consultants and supply chain for sampling, analytics and end-to-end-delivery of wastewater monitoring for public health • Worked closely with members of UK Research and Innovation research network (NWESP)
Data collection, analysis, sharing and use	• Samples collected from WWTW influent, non-sewered communities (stormwater systems and rivers) • Primary sludge and grab samples collected from industry sewage plants, prisons and hospitals	• Samples collected at the inflow of municipal WWTPs and pumping stations in the sewer network • Collection of 24-hour, high-frequency flow composite samples • Results shared on a weekly basis with the health authorities via direct communication and with the general public through dedicated web page	• Samples collected from influent, effluent, primary and waste activated sludge at WWTPs • Routine sampling covering 40–50% of the Turkey population, 25–95% of megacity Istanbul population • Routine sampling of touristic districts in Aegean and Mediterranean parts of Turkey	• Sampling from WWTPs, the sites providing coverage of around 70% of the population, and sampling from major cities at the community level • Data available on the Secure Research Service and on gov.uk • Whole-genome sequencing to identify lineage-defining mutations

(*Continued.*)

Table 1 | Continued

	South Africa	The Netherlands	Turkey	England
			• Routine sampling of some military areas	• Variants of concern and variants of interest tested in all WWTP and 50% of in-network sites weekly • Pilot programs collect samples from prisons, schools, managed quarantine facilities, halls of residence, food production factories • Collaboration with Scientific Pandemic Influenza Group to develop English prevalence models Integration with local response teams to sample and provide insights in areas with data gaps
Reach and impact on public health decision-making	• WBE surveillance not yet fully integrated into national COVID-19 surveillance programme • City of Cape Town and the Western Cape Provincial Department of Health incorporated WBE monitoring into their local responses	• WBE surveillance data has been evaluated in combination with conventional health surveillance data • Differences in trends observed via variations in clinical testing and wastewater testing, which was used by the health authorities to confirm or falsify apparent trends in the clinical testing data, the latter more prone to changes in testing behaviour and capacity ('everyone uses the toilet, not everyone uses the test facilities'. Also, city quarters differed in the ratio between reported cases and SARS-CoV-2 concentration in wastewater, suggesting underreporting in some city quarters. The health authority mobilised testing buses to these underreported areas to increase testing	• Early warning system established with routine systematic scanning in geographical regions • National roll-out	• National operational programme established • Wastewater concentration and sequencing data integrated into national situational awareness reporting and local health risk assessment processes • Wastewater database supports public health decision-making • Data frequently triggers public health action such as deployment and prioritisation of resources • Wastewater monitoring used with clinical testing for coordinated outbreak response

Programme design of the four case studies

The aim of establishing the national WBE surveillance programme in all the case studies was to provide scientific evidence regarding the prevalence of SARS-CoV-2 within communities. The programmes were further used as an early warning system to guide the governments' decision-making regarding their national responses which normally centred around allocation of resources and restriction measures to curb the spread of the virus. Once established, the programmes were also used to monitor the emergence of variants of concern in the population and the success of mitigation measures (e.g., targeted vaccination programmes, lockdowns, border control and quarantining).

In South Africa, the initial objective was to establish a national surveillance programme rollout to enhance the ability of the Department of Water and Sanitation to react to water supply and sanitation needs during COVID-19, and to integrate water quality and health data through a dedicated data platform. The programme was further re-designed to track the spread of

COVID-19 in communities, and South Africa is the only country among the four case studies to include the environmental surveillance in the context of non-sewered sanitation. In Turkey, the nationwide surveillance programme was initially established to evaluate the spread and extent of COVID-19 nationally before evolving into an early warning system for the government providing a routine systematic scanning of the different geographical regions. In England, in addition to the surveillance and early warning system the programme further provided public health intelligence and insight to guide the deployment of clinical resources. For the Netherlands, while the National Institute for Public Health and the Environment (RIVM) was focused on establishing a national programme of SARS-CoV-2 sewage surveillance (Lodder & de Roda Husman 2020), KWR focused on the development and finetuning of the analytical methodologies to detect SARS-CoV-2 in wastewater, observing patterns and trends and investigating how sewage surveillance could be used as a sensitive tool to monitor the circulation of the virus in the population, complementing clinical surveillance (Medema *et al.* 2020a).

With the viral mutation giving rise to new variants experienced by all the countries in the case study, the national programmes' scope was expanded to also include detection of signals of potential SARS-CoV-2 variants of concern (VOCs) and variants under investigation (VUIs) in WWTPs. The emerging COVID-19 variants are further reported using the publicly accessible government website and media to ensure public dissemination and awareness of the variants currently circulating in the communities and country. England is further working on detecting variants and mutation presence in near-source sites building on work undertaken by and in collaboration with the Natural Environment Research Council (NERC) Environmental Omics Facility (NEOF) (Hillary *et al.* 2021) and has incorporated co-occurrence analysis into its workflow (Jahn *et al.* 2021).

Programme coordination

Comparing the design and methodology of establishing the national programmes of the countries featured in the case studies, two programmes (England and Turkey) were initiated/owned by a national government department (e.g., health, environment or agriculture) and coordinated by a government entity or a research institute. Table 2 outlines the countries' funding and coordinating partnerships. The inclusion of national government representatives in the core partnership was expected to enable effective feedback and guidance to the national decision-making process. However, integration of WBE and surveillance into a national COVID-19 management strategy by governmental decision makers remains a challenge. The reason for this could be that as seen in Turkey, the overall national COVID-19 decision-making lies within the health ministry. Therefore, efforts should be made to promote understanding of the importance of WBE surveillance studies by health authorities. In South Africa, the programme is owned and coordinated by government entities. The WRC has continuously sought to secure government support through the Department of Water and Sanitation and the Department of Health, which are key for successful implementation of a nationwide rollout of the programme.

In The Netherlands, KWR initiated a monitoring process in six cities and the WWTP collecting wastewater from the Schiphol Airport in early 2020, and then decided to shift its focus towards three cities, namely Amsterdam, Utrecht and Rotterdam. In the course of 2020, the RIVM was mandated by the Ministry of Public Health to expand its national monitoring program to all WWTPs in the Netherlands. To avoid overlap, KWR pursued its research activities with the goal of further refining WBE and improving the understanding about the link between wastewater signals and virus circulation in the

Table 2 | WBE surveillance programme funders and coordinators at national and local level

Country	Coordinator(s)	Funder
England	United Kingdom Health Security Agency (UKHSA)	Department of Health and Social Care (DHSC), Department for Environment, Food & Rural Affairs (Defra)
The Netherlands	RIVM (national programme) KWR + partners (local projects)	Ministry of Health, Welfare and Sport (national programme) Top consortium of Knowledge and Innovation Water Technology and Health Holland, Foundation for Applied Water Research (STOWA), Erasmus Foundation
South Africa	National Institute of Communicable Diseases (NICD) in partnership with the South African Medical Research Council (SAMRC)	Water Research Commission (WRC), MRC and NICD
Turkey	Turkish Water Institute (SUEN)	Minister of Agriculture and Forestry

population (Medema *et al.* 2020a). Together with various partners, KWR set up a study in the city of Rotterdam, which involves the collection of high-resolution wastewater and epidemiological (e.g., swab testing, syndromic surveillance, genomic sequencing) data. At the time of writing, wastewater data was being collected both at the level of the WWTP influents and upstream at pumping stations, which serve specific neighbourhoods. More recently, the study also involves the monitoring of variants of concern through both targeted analyses and genome sequencing.

The multidisciplinary partnership model applied by all countries promoted national coordination, facilitated data sharing and complementarity with other national programmes implemented by the various health and water sector partners. All four countries included a mix of academic, industry and government experts in their partnership model. Although all countries implemented their programmes using a phased approach i.e., feasibility and/or proof of concept phase, pilot phase and nationwide programme phase, there was a distinct difference in the English and Dutch case studies.

In addition to the pilot to determine if WBE could provide a national and regional prevalence indicator which all countries undertook, England took a step further and implemented pilot projects to assess the feasibility of WBE in providing local public health insight in Exeter, and tested critical infrastructure and large buildings near-to-source through pilots monitoring schools and prisons in collaboration with academics from Universities of Middlesex, Cranfield, Newcastle and the UK Centre for Ecology and Hydrology (Gutierrez *et al.* 2021). More recently, SARS-CoV-2 monitoring has been undertaken in England at several managed quarantine facilities (for arrivals into the UK from any Red List country) to screen for variants of concern (VOC) or variants under investigation (VUI). These unique feasibility pilots were only seen in the England case study. On the other hand, The Netherlands, through KWR, was the only country initially which had a strong technical interest and dedicated efforts towards fine-tuning the analytical methodologies and getting a better understanding of the link between wastewater signals and virus circulation in the population to complement the clinical surveillance (Medema *et al.* 2020a). The England programme subsequently undertook a major research programme to optimize the methods to enable the rapid sequencing of VOCs and VUIs in wastewater alongside approaches for automated sample collection and on-site analysis.

Additionally, The Netherlands (through KWR) and England (through key government agencies, the Environment Agency and key academic partners), had a strong technical interest and dedicated efforts towards fine-tuning the analytical methodologies and getting a better understanding of the link between wastewater signals and virus circulation in the population to complement the clinical surveillance (Medema *et al.* 2020a).

In South Africa, a group of laboratories involved in the WBE and clinical surveillance collectively established a forum to communicate challenges and share experiences and lessons learnt. The group was named the South African Collaborative COVID-19 Environmental Surveillance System (SACCESS) network. Webinars were held to share methodologies for concentration, extraction and polymerase chain reaction (PCR) testing for the detection of SARS-CoV-2, and a compendium of methodologies was published (Corman *et al.* 2020). Below are the examples of the South African and Turkish WBE surveillance programme partnerships and networks. A similar network to SACCESS was developed in July 2020 in the UK, the National Wastewater-based Epidemiology Surveillance Programme (NWESP). The UK Natural Environment Research Council (NERC) funded network supported research into WBE sampling, analysis, and epidemiological model development, which directly supported the UKHSA, Defra and the Environment Agency of England, as well as the other devolved governments, as they established their surveillance programmes.

It is clear from all the case studies that strategic networks and partnerships are considered vital to the implementation of WBE surveillance programmes. In South Africa, the WRC categorised partnership needs into three categories, namely strategic, technical and knowledge partnerships. Ultimately, the biggest development with regards to establishing networks for WBE surveillance in South Africa to date has been the establishment of the SACCESS network. This network facilitates knowledge sharing and capacity building amongst its members, who also collaborated to standardise the methodology and sampling methods that are now used in many of the existing surveillance efforts.

Networks and partnerships

Organisations in all four case studies have prioritised the establishment of partnerships, collaborations and networks in their respective countries to ensure that the WBE programmes are national or regional initiatives. A collaborative COVID-19 Environmental Surveillance System (SACCESS) network for South Africa, KWR's international network and local partnership with Erasmus Medical Centre and the Municipal Health Service and others in Rotterdam, a thematic group for the 9th World Water Forum for Turkey, and Technical and Research networks in England were established to advance collaboration and partnerships among institutions and scientists working with COVID-19 surveillance in wastewater. South Africa and The Netherlands forged partnerships not only with scientific and knowledge organisations, which all four countries did, but also reached out to local governments and policymakers to be strategic partners for funding, implementation, knowledge dissemination, and use of the results from their programmes. All the institutions ensured that their programmes remain connected and engaged with the public health organisations so that the results from WBE can be used to save lives and manage the spread of the virus.

Communication and knowledge dissemination

The COVID-19 pandemic brought with it increased limitations to physical engagements, while at the same time catalysing the uptake and adoption of virtual engagement platforms such as video conferencing and online channels like websites, e-mails, broadcast and social media. Webinars are cited in three of the four country case studies as the preferred and dominant platforms used for knowledge sharing between the local and international science community. They enabled high participation and attendance of virtual events and facilitated global collaboration as well as extended reach beyond the science community to other key stakeholder groups specifically for the Netherlands, South Africa and Turkey teams.

The dominant channel for continuous programme updates, directed knowledge dissemination and official programme responses and news updates was website communication and via dashboards. This channel provided teams with a central, internally owned and controlled, publicly accessible repository for internal and external stakeholder engagement. The Turkish team further expanded its reach on website platforms by using its partnership with the Ministry of Agriculture and Forestry to upload dashboards and scientific papers on the ministry's website (https://covid19.tarimorman.gov.tr). KWR used the data collected in six cities to develop an analytical method to detect SARS-CoV-2 in wastewater, which was published in scientific paper in an early stage of the pandemic (Medema *et al.* 2020b). KWR, SUEN and Cranfield university published several scientific papers during 2020, targeting the scientific community.

The Netherlands, South Africa and Turkey teams referenced direct communication with government authorities, policy- and decision-makers, while both the Netherlands and England highlighted direct communication in engaging other scientists, water authorities and project teams.

Engagement with the public was done through broadcast media. Turkey focused specifically print media and television broadcast on prime time, which the team found to be highly effective. The South African context required the use of both television and radio broadcast mediums to extend reach to local communities, while print as a medium of communication was used once the lock-down restrictions were relaxed. Three of the four case studies (the Netherlands, Turkey and South Africa) included social media as a common dissemination tool for public dissemination both locally and internationally. Each case study illustrates that there is no one size fits all solution when it comes to building effective communication and that it is imperative that appropriate channels are used to reach relevant stakeholders.

Capacity building

Capacity building activities mentioned in the case studies predominantly took the form of publications and disseminating knowledge to the science community. The South Africa case study highlights capacity building initiatives embarked on by the SACCESS network and led by the WRC, who used a publication to facilitate the standardisation of sampling methodology and methods in South African surveillance programmes (Corman *et al.* 2020). The Netherlands, through KWR, published several papers on WBE methodologies, a best practice guide aimed at helping local teams and stakeholders to limit the spread of misinformation and support effective knowledge sharing. All country case studies mentioned the use of workshops, strategic meetings and dialogues as effective platforms for the sharing of learnings, experience and knowledge.

Targeted capacity building programmes were outlined in two case studies. KWR (Netherlands) highlighted capacity building programmes targeted at upskilling local authorities in wastewater testing capacities. Turkey outlined future plans by the COVID-19 thematic group for the 9th World Water Forum that aimed to build a global knowledge and experience sharing platform. The platform would focus on capacity building activities for low- and middle-income countries. As surveillance programmes in the various countries mature, there may be a more deliberate focus on capacity building that extends beyond the science community, the current focus is on building standards, developing tools for sampling, reporting and data sharing as well as upskilling local authorities.

The English programme was different in that it provided stimulus to industry to build commercial capacity, and automated sampling and analysis, via an initiative providing funding and collaborative working across sectors. This occurred in the

English (UK) water industry and via consultants and supply chain. These sectors were vital for sampling, analytics, and end-to-end-delivery of WBE for public health as capacity for analysis of SARS-CoV-2 abundance and genotyping of VOC and VUI increased.

Data collection, analysis, sharing and use

In all four countries, WWTP were sampled on a regular basis to test the presence of the COVID-19 virus genome. However, stormwater systems and urban rivers were also sampled in South Africa to determine the prevalence of COVID-19 in communities without sewer sanitation or using non-sewer sanitation, such as pit latrines.

The programmes in all countries targeted samples from most parts of the countries, via the network of researchers at their disposal. While testing for the prevalence and the spread of the virus was the main drive of these programmes, all countries showed interest in developing the early warning system or protocol to ensure the safety of vulnerable communities and to inform decision making by concerned institutions such as public health and transportation sectors. All the countries' programmes showed interest in studying the variants of the COVID-19 virus to advance science and support the development of effective vaccines.

Research and impact on public health decision-making

WBE has been implemented on a national scale in Turkey and the Netherlands. Sewage surveillance alone has not triggered any policy changes in the Netherlands, but has been used in combination with conventional swab testing as a piece of the puzzle for SARS-CoV-2 monitoring. In Turkey, scientific reports were submitted to the Ministry of Agriculture and Forestry before weekly cabinet meetings and the information was used to evaluate the need of local measures for pandemic control (Alpaslan Kocamemi *et al.* 2020). In South Africa, only the City of Cape Town and the Western Cape Provincial Department of Health have incorporated the WBE programme into their local responses. This is helping the City and province understand the emergence and patterns of infections. At the time of writing, however, efforts were underway to get municipalities that are considered COVID-19 hotspots to incorporate this approach into their local actions in managing this pandemic.

The use of real-time dashboard announcements, including simple and easily understandable maps, charts and graphs, combined with the national health interventions increases decision-makers' timely understanding of the findings of WBE studies and management of the disease. More importantly, proving that the early warnings provided by WBE surveillance correlate with data from clinical testing will increase the trust of decision-makers in the programme.

Discussion and recommendations from the four case studies

WBE surveillance for COVID-19 has proven to be an effective means of providing an early warning of the spread and trends of COVID-19 infections. Continued WBE sampling at priority sites will allow for the expansion of pandemic trend monitoring. Results indicated an increase over time in the viral load of the samples tested at surveillance sites, which corresponded to an increase in case numbers in hotspot areas.

Regular samples must, however, be taken over time to establish trends and baselines due to the inherent variability of sampling from smaller populations compared to a regional WWTP. Sampling in defined populations could provide a less invasive means of continuous screening. Where an increase in viral load is detected – signalling an early warning – additional clinical test methods could be rolled out in a timely way.

The lead-lag relationship between wastewater concentrations of SARS-CoV-2 RNA and case rates has not remained constant during the pandemic and more research is needed to understand the drivers of this variance (Wade *et al.* 2021). In England, the quantitative polymerase chain reaction qPCR) data are generated on average within 36 hours of sample collection, while in South Africa the time varies depending on the testing sites and location from labs, ranging between 2 to 4 days. In Turkey, the turn-around time for Istanbul is around 2 days, however, for the other cities in Turkey it takes up to 4–5 days since samples are all analyzed in center labs after all samples have been picked up and transferred. For the Netherlands, the Rotterdam-Rijnmond study showed that the lead time is related to the delay in clinical testing (delay time between disease onset day and day of testing). This delay was on average 6 days in the beginning of the second wave (which peaked in September 2020) and decreased to 1.5 days in December 2020 by the installation of large-scale testing facilities. When the clinical surveillance data of Rotterdam-Rijnmond were corrected for the testing delay, the clinical and sewage surveillance data overlapped, both in the rise and fall of the waves, which is to be expected since virus shedding is highest around onset.

Although wastewater surveillance provides a powerful tool to evaluate disease trends at the community level, its results must be combined with other public health data. It must, for example, be included in campaign-based and randomised testing of individuals (for the presence of pathogens or antibodies), clinical case reporting, mobile-based contact tracking and self-reporting systems (Boulos & Geraghty 2020). It is also important to consider how best to ethically and legally balance public health with civil liberties when handling epidemiological tracking information (Gostin *et al.* 2020).

In most case studies, communicating with public health authorities was mentioned as challenging due to the lack of expertise in the water sector and the different SARS-CoV-2 monitoring methods. In addition, public health officials were initially unfamiliar with the science behind WBE surveillance. As a result, 'translating' the wastewater data and communicating it in such a way that public health authorities can use it have proven taxing to researchers, as indicated in the Netherlands case study. Additionally, communication and knowledge dissemination have been demanding and time-consuming for the researchers and scientists working on the topic in all four case studies, which shows an area to better prepare for and support in the future.

An important outcome of the initial pilot studies in the UK/England and the monitoring of the six cities in the Netherlands is the improved trust in wastewater data to provide a reliable indication of SARS-CoV-2 trends. Comparisons were made with other epidemiological indicators, including large-scale longitudinal surveys and clinical testing data. In addition, work was undertaken to characterise the uncertainties in the data and determine how to account for them in reporting and modelling. Wastewater data were integrated into routine situational awareness reporting and local health risk assessment processes. It complemented other datasets and provided new data in areas where community infection levels were hard to measure. This approach of partnering with public health teams, including field epidemiologists and policymakers, helped ensure that the data provided were appropriate and useful.

The experience of WBE interventions has demonstrated its powerful contribution in complementing other health intervention efforts in managing this pandemic. It has shown:

- Consistent detection SARS-CoV2 RNA in wastewater samples from upstream and downstream WWTW
- Positive gene amplification observed in environmental (NSS) samples – i.e., river water samples
- WBE has proven to be a useful complementary surveillance tool for management of COVID-19
- Wastewater surveillance is a less invasive continuous screening approach
- Offers opportunity for correlation between increase in viral load and increase in case numbers with time
- Allowed the building of a robust collaborative platform of scientists, laboratories and WSIs

The WBE experiences and lessons have set up the potential for effective water quality surveillance of new and emerging contaminants and emerging pathogens, as well future tracking and management of the health of a population.

Some of the limitations of establishing and managing the WBE programme are: the insufficient funding to cover a wide range of the national programme, lack of coordination and buy-in by the key stakeholders limiting dissemination and uptake of the data and information generated during the surveillance programme, availability of test kits and equipment, number of laboratories registered and qualified to do the tests, standard for testing, collection etc.

CONCLUSION

Further work is needed to understand the impacts of network characteristics and population dynamics on SARS-CoV-2 detection in wastewater, especially in low-prevalence times. It is particularly important to standardise the methods for detection and quantifying the virus and other pathogens in wastewater. Based on the experiences in England and the Netherlands, the combination of wastewater monitoring with other epidemiological indicators (such as clinical detection and sequencing data, and longitudinal infection survey data) is recommended and already applied in practice to gain a full understanding of the changes in the prevalence of SARS-CoV-2 and its variants in communities and on a regional and national scale.

Communication efforts should be aimed at transparency and effectiveness to fully convey the strength of the method to those unfamiliar with this type of environmental monitoring. WBE surveillance offers a potential early warning system for the spread of SARS-CoV-2 infections. Surveillance of defined communities can be used to direct community screening efforts and alert medical authorities to potential increases in patient numbers. This may also provide valuable input for dashboards tracking or monitoring the COVID-19 pandemic. Wastewater testing can be useful in monitoring the prevalence of COVID-19 infections across the globe and alludes to the application of such a monitoring system to other factors affecting human health. Furthermore, the manner in which the programmes were coordinated presents useful lessons for national responses to future pandemics and on-going non-COVID related public health issues.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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