Digital solutions for continued operation of WRRFs during pandemics and other interruptions

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1INTRODUCTION

The ongoing worldwide crisis due to the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) outbreak is the first modern pandemic, causing severe problems for human health, wealth, and societal well-being. COVID-19 is a respiratory disease caused by the SARS-CoV-2 (WHO, 2020a), and approximately 220 countries have been affected by COVID-19 (WHO, 2020b). Many regional and global emergency measures have been taken within a short period of time to protect public health, which would otherwise have taken years to implement (Harari, 2020). Global innovation, including innovations in policies, is the key to minimize the damages inflicted by this pandemic to the society (Gates, 2020). Wastewater treatment plants (WWTPs) are increasingly regarded as water resource recovery facilities...
(WRRFs) to reflect the circular economy perspectives in the water sector (Solon et al., 2019; van Loosdrecht & Brdjanovic, 2014) and are principal actors in improving water quality and mitigating public health risks. During the current pandemic, significant concerns have been raised regarding the safety of wastewater sanitation and sewage systems due to the possibility of transmission of viruses (Venugopal et al., 2020). Our current practical and theoretical knowledge on the fate and transmission of SARS-CoV-2 in sewages and WRRFs is insufficient to draw reliable conclusions. This puts extra pressure on wastewater treatment utilities to ensure the safe, continuous, and effective operation of WRRFs.

The implementation of digital technologies in the water sector can potentially lead to solutions for long-lasting challenges faced by the water industry. However, the water sector still lags behind other societal sectors in adopting advanced digital technologies (Messner et al., 2019). A predictive analysis by the McKinsey Global Institute suggested that 80% of the water utilities in developed countries are expected to adopt digital solutions such as water consumption tracking, leakage detection and control, smart irrigation, and water quality monitoring by 2025, whereas these values are reduced to only 50% in developing countries (Woetzel et al., 2018). It is noted that the pandemic has altered water demand and consumption patterns in the urban water systems. Therefore, sensors, on-line instrumentation, and control devices can provide additional data sources required for optimal management of water systems (Verdaguer et al., 2018).

Regardless of the threat of viruses to human beings, the pandemic has created critical challenges to WRRF related to technical, operational, maintenance, and management aspects, and these are discussed in this perspective paper. In addition, the paper explores how sensor application and automation can play a vital role in providing safe and uninterrupted operations. This paper also highlights resources needed for emergency responses, resiliency, and mitigation during a pandemic such as COVID-19 as well as during emergency situations such as severe weather events, catastrophic disasters, and hurricanes.

2 | SURVEYS ON CHALLENGES IN WRRF OPERATIONS DURING A PANDEMIC AND POTENTIAL RISKS

In this study, 17 full-scale WRRFs were surveyed in order to identify the key challenges they faced during the COVID-19 pandemic and their adaptive actions to prevent uninterrupted operations to meet effluent water quality limits. The survey was conducted by interviewing operations and maintenance staff, plant engineers, and plant managers. The survey conducted for this study was a voluntary opinion survey, rather than a random, representative sample. The survey campaign focused on two different issues: (a) technical, operational, and maintenance issues and (b) personnel/staff management issues observed during the pandemic.

2.1 | Survey methods

The facilities surveyed in this study are located in North America (n = 15), Europe (n = 1), and Australia (n = 1). The plants were categorized into different annual average daily flow ranges such as 1 to 10, 10 to 20, 20 to 30, 30 to 40, 40 to 60, and above 100 million gallons per day (MGD). The specific locations and names of the plants have not been included in this paper observing their request for anonymity. Table 1 summarizes the treatment capacity, liquid treatment processes, effluent limits, and level of process of automation of the 17 WRRFs surveyed in this study. Most of the plants have year-round total suspended solids (TSS), biochemical oxygen demand (BOD), and nutrient effluent limits (nitrogen and phosphorus) requirements. Some plants have only effluent TSS and BOD requirements depending on the receiving water body regulations. The level of process automation in each facility was surveyed to understand its role during the pandemic on facility operations. For the purpose of the survey, the level of process automation mostly focused on the availability of sensors. All the plants surveyed are implementing solids retention time (SRT) control using mixed liquor suspended solids (MLSS) data. Studies found that 24% of the plants surveyed had real-time instruments for online monitoring of chemical oxygen demand (COD), ammonia, nitrate, phosphorus, dissolved oxygen (DO), and TSS. Some of the plants implemented DO control, whereas others were using ammonia-based aeration control (ABAC) and ammonia versus NOx (AVN) control to minimize aeration costs. Two out of the 17 surveyed WRRFs were being run based on manual operation. The survey questions are explained in the supporting information. Each participant contributed to the survey had options to provide multiple choice response (yes or no) and open comment response for survey questions, and based on the feedback, the survey data are analyzed.

2.2 | Technical, operational, and maintenance challenges

Most of the facilities surveyed in this study experienced some level of disruptions in technical, operational, and
maintenance aspects during the COVID-19 pandemic. Figure 1 presents a summary of these issues. Survey results indicated that 24% of WRRFs had equipment maintenance problems due to requirements to work remotely during the pandemic (Figure 1). Because a part of the maintenance staff was sent home, the complete schedule for plant maintenance could not be met. Crews had to prioritize which equipment should be maintained. Moreover, extending maintenance frequency put equipment at risks of failure. As a result, those plants fell behind regarding maintenance which eventually resulted in increased equipment break downs. This incurred extra costs as noted by 24% of WRRFs surveyed (Figure 1). Most of the facilities (76%) were well prepared by having in stock spare parts of equipment for required maintenance; however, some plants experienced delays in the

| No. | WRRF | Treatment capacity (MGD) | Liquid treatment process | Permit limit for N and P* | Level of process automation |
|-----|------|--------------------------|--------------------------|--------------------------|-----------------------------|
| 1   | Plant A | 1 to 10 | Oxidation ditch with selector zone | N | | |
| 2   | Plant B | Biological nutrient removal using intermittent aeration | No requirement | | | |
| 3   | Plant C | Biological nutrient removal system | N, P | | | |
| 4   | Plant D | 5-stage Bardenpho | N, P | | | |
| 5   | Plant E | 10 to 20 | Biological nutrient removal system using oxidation ditches | N, P | | | |
| 6   | Plant F | 5-stage Bardenpho | N, P | | | |
| 7   | Plant G | 20 to 30 | A/O | N, P | | | |
| 8   | Plant H | Biological nutrient removal system with powdered activated carbon addition | N, P | | | |
| 9   | Plant I | 5-stage Bardenpho | N, P | | | |
| 10  | Plant J | 5-stage Bardenpho | N, P | | | |
| 11  | Plant K | 30 to 40 | Primary treatment | No requirement | | | |
| 12  | Plant L | Biological nutrient removal system | N, P | | | |
| 13  | Plant M | 40 to 60 | A/O | No requirement | | | |
| 14  | Plant N | Conventional activated sludge | N | | | |
| 15  | Plant O | > 100 | Selector zone and low DO nitrification systems | N | | | |
| 16  | Plant P | Trickling filter and aeration basin | N | | | |
| 17  | Plant Q | High-rate activated sludge and nitrification/denitrification | N, P | | | |

Note: Seventeen full-scale plants were surveyed for this study. Each plant has effluent BOD and TSS requirement. Plants K and M have manual operation. Abbreviations: ABAC, ammonia-based aeration control; AVN, ammonia versus NOx control.
shipments of spare parts, and some vendors suspended maintenance-related site visits.

The most significant obstacle in surveyed WRRFs encountered during this COVID-19 was the quality of data collected by the online instrumentation. About 35% WRRFs observed poor data quality issues during the pandemic (Figure 1). Due to reduced personnel and selective maintenance tasks, the online instruments were not cleaned and maintained as frequently. This resulted in signal drift and sensors calibration issues. In addition, personnel had to be placed on unfamiliar assignments which meant that not all had trainings on the systems that run the plant control such as ABAC, AVN, and online SRT. As previously mentioned, the main issue with process controls was instrument maintenance.

As industries and companies shut down during the pandemic, the plant flows and loads were reduced dramatically in some places, and 18% of WRRFs surveyed in this study experienced this problem (Figure 1). The load reduction impaired the biological treatment processes as reported by 12% of WRRFs (Figure 1). In addition, in the first week of the shutdown during the pandemic, 24% of surveyed WRRFs identified that they were receiving illicit discharges from industrial cleaning operations or materials that might increase toxic pollutants which eventually resulted in operational upsets (Figure 1).

The survey campaign also indicated that about 47% of WRRFs experienced delays in chemical supply during the pandemic. This was because travel restrictions impacted the chemical supply chain (Figure 1). On the other hand, 53% of WRRFs responded that they had enough chemical supply to prevent potential shortages.

### 2.3 Personnel management challenges

Although the city/state/country went into lockdown for the pandemic, some plants were in the middle of construction for improvements, rehabilitation, or expansion. Every facility experienced an immediate impact on their personnel management specifically for operations and maintenance staff which are considered essential workers. Figure 2 presents the overall survey results from WRRFs on personnel management issues during the COVID-19 pandemic.

Survey results showed that COVID-19 emergency measures included a new set of personnel management rules and health and safety measures for WRRFs operations. It was found that 71% of WRRFs had emergency personnel management rules already in place (Figure 2). However, one plant reported that they had no procedure on how to enforce the new rules and how to select the personnel that would work from site or home. All WRRFs had health and safety rules and guidelines at the beginning of the pandemic (Figure 2). Masks were mandatory, and frequent hand washing practices had been encouraged in all facilities. In addition, safety shields and personal protective equipment (PPE) were provided to operations and maintenance staff for health protection and for providing a safe working environment. Maintaining physical distances was imposed, and wiping common areas with disinfectants was also strongly encouraged. If any potential COVID-19 exposures were known, immediate self-quarantine was imposed which created some staffing issues.

According to the survey results, about 41% of WRRFs had difficulties in scheduling shifts for operators...
(Figure 2). The health and safety measures required extra time to check everyone at work which reduced shift start times. Supervisors were rotated, and when they came back to the sites, they needed additional time to catch up. The plant staff did not have any in-person meetings because all meetings went virtual. Some plants reduced the direct contact with vendors during the pandemic time and allowed limited staff in one vehicle for the travel.

The maintenance workers in some plants were given incentives for coming to work such as working half time was paid in full plus every shift earned certain hours of vacation. About 41% of WRRFs reported that they provided free lunch to staff for coming to the plant to ensure that the plant’s operation was not impacted by the pandemic (Figure 2).

One of the plants reported that they had already dealt with other infectious disease outbreaks such as H1N1 and SARS and had already put several emergency procedures in place. During the COVID-19 outbreak, personnel, especially the staff working in open sewers, asked how infectious the aerosols were in wastewater. Plant management reached out to the Water Environment Federation (WEF) and tried to collect as much scientific information as was available. They mentioned that WEF publications and webinars were beneficial and they conveyed the facts to their personnel.

3 | AUTOMATION AND SENSOR APPLICATION IN WRRF

The COVID-19 pandemic and the resulted social confinement situation showed that process monitoring and automation are vital for operation of municipal WRRFs. It might be anticipated that any other possibilities of future pandemic may lead to recurrence of the confinement situation that may lead to interruption/complete shutdown of WRRFs. In this case, the main issue for the wastewater management would be how to ensure the continuity of the water sanitation through uninterrupted duty of equipment, resource supply, and availability of the essential operators. That requires taking a closer look to the potential for digitalization in wastewater treatment and the role of online monitoring and automation in WRRFs operation and rethinking how to benefit from it in long-term confinement situations.

3.1 | How automation is playing a role in WRRF operation

Automation, artificial intelligence (AI), and data mining through digitalization enable the water sector to extend resources, reduce non-revenue water, expand infrastructure life cycles, and improved financial security. This would allow utilities to become more resilient, innovative, and efficient. Digitalization encompasses monitoring and forecasting of the plant performance, data processing, the use of digital twins, and further blockchain applications (Garrido-Baserba et al., 2020; Sarni et al., 2019). Sensors are mainly used in WRRFs to monitor the system and collect real-time data on water quality, flowrates, pressures, water levels, and so forth to provide information to the plant operators about the state and performance of the plant and evaluate operation. This gives the operators the opportunity to prepare for and react to operational problems, water quality issues, and adjusting the plant’s operation remotely to minimize the negative impacts or failure. The collected data can also be used to analyze the performance evaluation of specific events or major trends. The second main use of the sensors is to provide data for automatic control systems. Reliable online sensor data can directly be used in control strategies to improve efficiency of the plant (Vanrolleghem & Lee, 2003). Hence, sensor accuracy is crucial for successful process control and monitoring. Sensor application and automation provide benefit by reducing aeration energy cost. It is possible to adjust the required DO concentration in the biological reactor to meet the effluent criteria based on the influent load and effluent concentrations resulting in reduced energy consumption for different processes (Le et al., 2019; Rieger et al., 2019; Schraa et al., 2020). Apart from that, wet-weather flow management, external carbon or alkalinity addition for improved nitrogen removal, chemical addition for phosphorus removal, sludge handling, and disinfection processes can be automated successfully with minimal attention from remote operators (Manoli et al., 2018; Mbamba et al., 2019; Sandino et al., 2018).

Monitoring data from sensors are also used by consultants to audit treatment plants, calibrate model for process optimization, or evaluation of different operational scenarios (Petersen et al., 2002). Models are used to replicate the treatment system virtually through digital twin that can be directly connected online to the WRRFs or can be run by automated interfaces to improve the performance of the system (DHI Group, 2019; Dynamita, 2020). Digital twins enable dynamic process simulation to help optimization, reduce risk, and support operator training; however, this tool has not yet been widely used for real-time optimization applications in WRRFs. Figure 3 presents an overview of the direct and indirect benefits of using sensors and automation in WRRF.
3.2 Opportunities of automation and sensor usage in WRRF operation during pandemic

It is anticipated that the pandemic and the resulting social confinement may lead to a recurrence of the lock downs that may lead to interruption of WRRFs operations. To guarantee uninterrupted equipment operation, resource supply, and availability of essential operators, it is necessary to take a closer look at the potential of digitalization in wastewater treatment. The global threat of COVID-19 is pushing the wastewater sector to reconsider all aspects of digitalization and accelerate its integration. Sensors, automation and control, remote sensing, and the use of digital twins are some of the key elements within this context. Sensor usage together with automation gives the opportunity to remotely monitor the processes and keep an eye on the system without the obligation of physical presence in the plant. The critical operations/processes that need continuous monitoring can be equipped with remote sensing and alarms that can be accessed by remote management or in the central control station. For example, cell phones can be used to receive text alarms from programmable logic controllers if any equipment failure occurs. This would help the plant operators to reduce the need for 24 h of physical manpower. Thus, it helps to optimize labor and employee resources as well.

It has been shown that automation can improve the efficiency of wastewater treatment systems using control and optimization. In addition, it helps to decrease operational costs by reducing energy and chemical consumption. One critical issue is that automation depends on real-time data from sensors and other instruments. Maintenance of most of the instruments requires manual labor (cleaning, calibration, etc.) that needs to be performed frequently. Thus, physical presence in some level is required to make sure data quality is not impacted during an emergency situation. Survey results from this study also suggested that all facilities agreed that manual labor is required for maintaining online instrument calibration and cleaning in order to collect reliable data (Table 2).

The results obtained from the survey campaign identified that having online instruments on the individual wastewater streams—most importantly from the major industrial dischargers—would have helped them identify the load reduction without waiting to be informed by the industry representatives. All facilities agreed that digitalization and automation using sensor application would provide operational flexibility during the pandemic. Additionally, 65% of those facilities agreed that digitalization could help their facility operations while working from home (Table 2).

In the future, proper utilization and implication of automation in WRRF operation require education and training for operators. A minimum number of staffing requirements would need to be maintained during the emergency to confirm the uninterrupted operation. Survey campaign results suggested that evaluation of more process scenarios under reduced/erratic flows and loads...
need to be considered to anticipate process performances and develop pre-plans to handle those situations. In addition, facilities can also develop pre-planned action plans specifically for managing construction activities during an emergency. Figure 3 presents an overview of the direct and indirect benefits of using sensors and automation in WRRFs operation during a pandemic.

4 | RESOURCES NEEDED FOR EMERGENCY RESPONSE IN WRRF

Emergency response during a pandemic is a coordinated and planned process. Proper planning using available resources can lessen the impact of an emergency. Therefore, it is critical to identify all the required resources to support emergency responses in the WRRF. Facilities should have their own standardized response and recovery protocol to prevent, minimize, and mitigate damages resulting from emergencies and pandemics.

Following the past global outbreaks such as the avian flu in 2003 and swine flu in 2009, many WRRFs created pandemic resilience plans based on best practices and their experiences during that time. Moreover, most water systems already have continuity plans as part of their best management practices (Benedetti et al., 2013). Therefore, during a pandemic, WRRFs can review and update those plans and stay in close contact with their local health department and regulatory agency as pandemics are dynamic situations and can evolve rapidly. WRRFs need the most updated information to make decisions that are right for their utility based on the impacts to their specific community.

The United States Environmental Protection Agency (US EPA) provides much of the necessary information for general preparedness purposes during a pandemic. These resources are provided to support the operational needs of WRRFs including maintaining adequate staffing and laboratory capacity. The US EPA recommends that States work with their utilities to review their continuity plans during a pandemic (US EPA, 2020). If the need for resources arises for any reason, the Water and Wastewater Agency Response Network (WARN) provides WRRFs with the means to quickly obtain help in the form of personnel, equipment, materials, and associated services from other WRRFs to restore critical operations impacted during any type of emergency situation. WARN comprises mutual aid and assistance among WRRFs within a state that responds to and recover from emergencies by sharing resources with one another. However, although States require to send personnel, equipment, and commodities to other States to help during the governor-declared state of emergency, Emergency Management Assistance Compact (EMAC) can be used as an essential resource. It is noted that EMAC is the only congressionally ratified mutual aid and assistance between all states along with District of Columbia, the U.S. Virgin Islands, Puerto Rico, and Guam.

The Circuit Riders program funded by the US Department of Agriculture is another great resource for Rural WRRFs that experience operational, financial, or managerial issues during pandemic. Under this program, certified Circuit Riders are deployed to provide technical assistance and expertise to support systems in need (Cowan, 2016). Organizations such as the Rural Community Assistance Partnership (RCAP) and the National Rural Water Program (NRWA) are also great resources that provide technical assistance through Circuit Riders that work onsite with utility system personnel to troubleshoot problems and respond to the pandemic (McNabb, 2017). Furthermore, US EPA provides Pandemic Incident Action Checklist that is comprised of three different “rip and run” checklists to help water utilities prepare for, respond to, and recover from a pandemic. Each checklist provides examples of actions that WRRF can also consider. It should be noted that, if sufficient resources are not found, State water operator program offices can be contacted for information for help in finding resources for WRRF operations.

Besides EPA, WARN, EMAC, NRWA, American Society for Civil Engineers (ASCE) has policy statement of 499 and 500 which were established in 2003 for emergency preparedness and response and infrastructure resilience act, respectively (Sowby, 2020). The policy statement of 499 has been used for engineering services during COVID-19 pandemic. The policy statement 500 provides guidelines for infrastructure vulnerabilities. Infrastructure resiliency is well exercised for disruption.
like earthquakes and hurricanes but not for pandemic situation. This is because pandemic poses different resilient challenges for infrastructure in terms of scale, acuteness, recovery, duration, social, and economic complications (Sowby, 2020). Therefore, it is crucial that WRRFs, water treatment utilities, and other municipal utilities can collaborate to identify the challenges, weakness, and solutions for emergency situation like COVID-19 and utilize available resources for emergency response and resiliency.

### 5 | RETHINKING RESILIENCY AND MITIGATION IN WRRF DURING A PANDEMIC

The current pandemic is creating an opportunity for WRRFs to explore and rethink their existing infrastructure, technologies, and services. The experience from the pandemic will inform WRRFs on how to become water resilient through lessons-learned in an unexpected situation. Resiliency of water, sanitation, and hygiene systems are critical to handle uncertainties like COVID-19 to improve worker safety and minimize water scarcity and pollution. Investment in wastewater treatment is essential to protect communities and ecosystems, to safeguard public health against biological hazards such as COVID-19, and to ensure safe recycling of water, energy, and nutrient resources (Sadoff & Smith, 2020). Poch et al. (2020) suggested that digital revolution can be accelerated by providing economic support to WRRFs in terms of asset, resource, and energy management. Similar observation was reported by Zechman Berglund et al. (2021), and they suggested to increase usage of smart technologies, engineering education, and management of water infrastructure in utilities. In addition, integration of beneficial knowledge, information sharing, and data sharing between WRRFs can significantly enhance their resiliency and mitigation technique based on insights gained from the pandemic.

It is inevitable now that WRRFs will need to develop necessary plans and programs for safe plant operations with minimal interruption during pandemic situations. One practical way to become resilient is to adopt automation and sensor-based plant operation which can assist with social (physical) distancing between operational staff. However, unplanned staff absences cannot be avoided, and therefore, WRRFs need to rethink how to become more resilient during pandemic. Warden and Naylor (2020) reported that segregation and effective communication between the operations and maintenance department are key strategies to avoid operational risks. If any member gets sick from either department, effective remote communication is one of the key processes to keep other members safe so that labor skills from both operations and maintenance can be available during challenging situations. In addition, offsetting work shifts of operational and maintenance teams may reduce the risk of physical contact between them resulting in less chance of operational interruption. In fact, plants that provide options for temporary accommodation or shelter in place for operators can reduce infection exposure outside of work. Overall, the traditional work practices need to be altered and utilizing technology as central pathways for adaptation and coping mechanisms can provide effective work environment during pandemic (Lawson et al., 2021). Moreover, Warden and Naylor (2020) stated that the smart utilization of communication technology can also be an effective mitigation strategy. The online video conference meeting is now considered as a standard way of communication to avoid physical contact between plant staff members. However, additional training for operators on how to manage and operate the plant using remote access while maintaining data security is critical. Thus, adopting and implementing modern automation and sensor application-based platforms can provide the access to all necessary data and information. This results in operations without minimal disruption during a pandemic or any other disaster when staff work from home and are unable to attend on-site.

During the pandemic, a systematic screening process used as an early warning system to detect SARS-CoV-2 in raw wastewater can be developed (WRF, 2020). These systems can provide public health information connected to regional population. The early detection system can then be used to inform response measures such as quarantine of communities or targeted monitoring (Bivins et al., 2020; Mallapaty, 2020; Medema et al., 2020; Poch et al., 2020). Thus, many research institutions have been involved with wastewater surveillance program for SARS-CoV-2 detection (Arnaud, 2020; Lodder & Husman, 2020). Innovation in sensor development to detect this virus can also help become resilient before any health disaster happens.

### 6 | CONCLUSIONS

Digital water technologies can assist and support wastewater utilities to figure out and pinpoint their operational and monitoring gaps, resulting in significant improvement in economic and environmental aspects. In addition, these technologies can mitigate the risks of interruption. Moreover, when utilities face challenges in recruiting skilled staff resulting in reduced manpower,
digital technologies are the key to continue operation by doing more with less manpower. The advancement of data analytics and digital water strategies are essential components of WRRFs operations during a crisis like the COVID-19 pandemic. The potential growth of digital water technologies in WRRFs operation can transform the operational strategy and to mitigate the risk of failure during a crisis like the pandemic.

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AUTHOR CONTRIBUTIONS
Arifur Rahman: Conceptualization; data curation; formal analysis; investigation; methodology; resources; supervision. Evangelia Belia: Conceptualization; investigation; methodology; resources. Gamze Kirim: Data curation; investigation; methodology; resources. Mahmudul Hasan: Data curation; investigation; methodology; resources. Sina Borzooei: Investigation; methodology. Domenico Santoro: Resources. Bruce Johnson: Conceptualization; investigation; methodology; resources.

CONFLICT OF INTEREST
The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT
n/a

REFERENCES
Arnaud, C. (2020). Monitoring COVID-19 in sewage, viewed January 2, 2021. https://acen.ces.org/environment/water/Monitoring-COVID-19-sewage/98/i45
Benedetti, L., Langeveld, J., Comeau, A., Corominas, L., Daigter, G., Martin, C., Mikkelsen, P. S., Vezzaro, L., Weijers, S., & Vanrolleghem, P. A. (2013). Modelling and monitoring of integrated urban wastewater systems: Review on status and perspectives. Water Science and Technology, 68(6), 1203–1215. https://doi.org/10.2166/wst.2013.397
Bivins, A., North, D., Ahmad, A., Ahmed, W., Alm, E., Been, F., Bhattacharya, P., Bijlsma, L., Boehm, A. B., Brown, J., & Buttiglieri, G. (2020). Wastewater-based epidemiology: Global collaborative to maximize contributions in the fight against COVID-19. Environmental Science & Technology, 54(13), 7754–7757. https://doi.org/10.1021/acs.est.0c02388
Cowan, T. (2016). An overview of USDA rural development programs. Washington, DC: Congressional Research Service.

DHI Group. (2019 December 19). https://blog.dhigroup.com/2019/12/19/wastewater-treatment-how-can-digital-twin-modelling-play-a-crucial-role-in-wwtp-operations/

Dynamita. (2020). SUMOLATOR: Dynamita's Digital Twin Toolkit. Garrido-Baserba, M., Corominas, L., Cortés, U., Rosso, D., & Poch, M. (2020). The fourth-revolution in the water sector encounters the digital revolution. Environmental Science & Technology, 54, 4698–4705. https://doi.org/10.1021/acs.est.0b04251

Gates, B. (2020). The first modern pandemic [WWW document]. gatesnotes.com. URL https://www.gatesnotes.com/Health/Pandemic-Innovation (accessed 7.31.20).

Harari, Y. N. (2020). Yuval Noah Harari: the world after corona-virus|Free to read [WWW Document]. URL https://www.ft.com/content/19d90308-6858-11ea-a3c9-1fe6fedcca75 (accessed 7.31.20).

Lawson, E., Bunney, S., Cotterill, S., Farmani, R., Melville-Sheree, P., & Butler, D. (2021). COVID-19 and the UK water sector: Exploring organisational responses through a resilience framework. Water Environment Journal. https://doi.org/10.1111/wej.12737

Le, T., Peng, B., Su, C., Massoudieh, A., Torrents, A., Al-Omari, A., Murthy, S., Wett, B., Chandran, K., de Barbadiello, C., Bott, C., & de Clippeleir, H. (2019). Nitrate residual as a key parameter to efficiently control partial denitrification coupling with anammox. Water Environment Research, 91, 1455–1465. https://doi.org/10.1002/wer.1140

Lodder, W., & Husman. A. (2020). SARS-CoV-2 in wastewater: Potential health risk, but also data source. Viewed February 8, 2021. https://www.thelancet.com/journals/langas/article/PIIS2468-1253(20)30087-X/fulltext

Mallapaty, S. (2020). How sewage could reveal true scale of coronavirus outbreak. viewed January 25, 2021. https://www.nature.com/articles/d41586-020-00973-x

Manoli, K., Sarathy, S., Neofotistos, P., & Santoro, D. (2018). Pilot-scale validation and performance testing of advanced dose control for chemical disinfection of wastewater. Proceedings of the Water Environment Federation Technical Conference. New Orleans, Louisiana. 2179-2185.

Mbamba, C., Kazadi, E., Lindblom, X., Flores-Alsina, S., Tait, S., Anderson, R., Saagi, D., Batstone, J., Gernaey, K. V., & Jeppsson, U. (2019). Plant-wide model-based analysis of iron dosage strategies for chemical phosphorus removal in wastewater treatment systems. Water Research, 115, 12–25.

McNabb, D. E. (2017). Federal Regulators of the resource. In Water resource management (pp. 133–162). Cham: Palgrave Macmillan.

Medema, G., Heijnis, L., Elsinga, G., Italiaander, R., & Brouwer, A. (2020). Presence of SARS-CoV-2 RNA in sewage and correlation with reported COVID-19 prevalence in the early stage of the epidemic in the Netherlands. Environmental Science & Technology Letters, 7(7), 511–516. https://doi.org/10.1021/acs.estlett.0c00357

Messner, D., Nakicenovic, N., Zimm, C., Clarke, G., Rockström, J., Aguiar, A. P., Boza-Kiss, B., Campagnolo, L., Chabay, I., & Collste, D. (2019). The digital revolution and sustainable development: Opportunities and challenges-report prepared by the world in 2050 initiative. Luxemburg, Austria: International Institute for Applied Systems Analysis (IIASA).
Poch, M., Garrido-Baserba, M., Corominas, L., Perelló, M., Petersen, B., Gernaey, K., Henze, M., & Vanrolleghem, P. A. (2002). Evaluation of an ASM1 model calibration procedure on a municipal-industrial wastewater treatment plant. *Journal of Hydroinformatics*, 4, 15–38. https://doi.org/10.2166/hydro.2002.0003

Poch, M., Garrido-Baserba, M., Corominas, L., Perelló-Moragues, A., Monclus, H., Cermérón-Romero, M., Melitas, N., Jiang, S. C., & Rosso, D. (2020). When the fourth water and digital revolution encountered COVID-19. *Science of the Total Environment*, 744, 140980.

Rieger, L., Jones, R. M., Dold, P. L., & Bott, C. B. (2019). Ammonia-based aeration control with optimal SRT control: Improved performance and lower energy consumption. *Water Environment Research*, 79(1), 63–72.

Sadoff, C., & Smith, M. (2020). Water in the COVID-19 Crisis: Response, recovery, and resilience. viewed February 5, 2021. https://nssp.ifpri.info/2020/06/15/water-in-the-covid-19-crisis-response-recovery-and-resilience/

Sandino, J., Siczka, J., & Thewes, D. (2018). Bells lane WWTP: Successfully integrating and automating multiple unit processes for effective remote CSO management. *Proceedings of the Water Environment Federation Technical Conference*. New Orleans, Louisiana. 1297-1312.

Sarni, W., White, C., Webb, R., Cross, K., & Glotzbach, R. (2019). *Digital water: Industry leaders chart the transformation journey*. International Water Association.

Schröer, O., Rosenthal, A., Wade, J., Rieger, L., Miletic, I., & Alex, J. (2020). Assessment of aeration control strategies for biofilm based partial nitritation/anammox systems. *Water Science and Technology*, 81(8), 1757–1765.

Solon, K., Volcke, E. I., Spérandio, M., & van Loosdrecht, M. C. (2019). Resource recovery and wastewater treatment modelling. *Environmental Science: Water Research & Technology*, 5, 631–642.

Sowby, R. B. (2020). Emergency preparedness after COVID-19: A review of policy statements in the US water sector. *Utilities Policy*, 64, 101058. https://doi.org/10.1016/j.jup.2020.101058

US EPA. (2020). Water utility resources for the COVID-19 pandemic. viewed September 21, 2021. https://www.epa.gov/coronavirus/water-utility-resources-covid-19-pandemic

van Loosdrecht, M. C., & Brdjanovic, D. (2014). Anticipating the next century of wastewater treatment. *Science*, 344, 1452–1453. https://doi.org/10.1126/science.1255183

Vanrolleghem, P. A., & Lee, D. S. (2003). On-line monitoring equipment for wastewater treatment processes: State of the art. *Water Science and Technology*, 47, 1–34. https://doi.org/10.2166/wst.2003.0074

Venugopal, A., Ganesan, H., Raja, S. S. S., Govindasamy, V., Arunachalam, M., Narayanasamy, A., Sivaprakash, P., Rahman, P. K., Gopalakrishnan, A. V., & Siama, Z. (2020). Novel wastewater surveillance strategy for early detection of COVID–19 hotspots. *Current Opinion in Environmental Science & Health*, 17, 8–13.

Verdaguer, M., Molinos-Senante, M., Clara, N., Santana, M., Gernjak, W., & Poch, M. (2018). Optimal fresh water blending: A methodological approach to improve the resilience of water supply systems. *Science of the Total Environment*, 624, 1308–1315. https://doi.org/10.1016/j.scitotenv.2017.12.204

Warden, W., & Naylor, J. (2020). Helping water utilities mitigate COVID-19 challenges. Viewed February 1, 2021. https://www.wef.org/wef-waterblog/wef-waterblog/helping-water-utilities-mitigate-covid-19-challenges/

WHO. (2020a). WHO coronavirus disease (COVID-19) dashboard [WWW document]. https://covid19.who.int (accessed 8.5.20).

WHO. (2020b). Naming the coronavirus disease (COVID-19) and the virus that causes it [WWW document]. https://www.who.int/emergencies/diseases/novel-coronavirus-2019/technical-guidance/naming-the-coronavirus-disease-(covid-19)-and-the-virus-that-causes-it (accessed 8.3.20).

Woetzel, J., Remes, J., Boland, B., Lv, K., Sinha, S., Strube, G., Means, J., Law, J., Cadena, A., & Von der Tann, V. (2018). *Smart cities: Digital solutions for a more livable future* (pp. 1–152). N. Y. NY USA: McKinsey Glob. Inst.

WRF. (2020) Wastewater surveillance of the COVID-19 genetic signal in sewersheds. Viewed January 26, 2021. https://www.waterrf.org/sites/default/files/file/2020-06/COVID-19_Water_SummitHandout-v3b.pdf

Zechman Berglund, E., Thelemaque, N., Spearling, L., Faust, K. M., Kaminsky, J., Sela, L., & Kadinski, L. (2021). Water and wastewater systems and utilities: Challenges and opportunities during the COVID-19 pandemic. *Journal of Water Resources Planning and Management*, 147(5), 02521001. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001373

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Additional supporting information may be found in the online version of the article at the publisher’s website.

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