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When the fourth water and digital revolution encountered COVID-19

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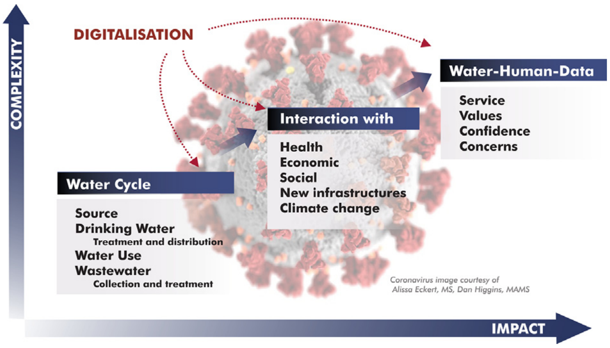
HIGHLIGHTS

- The impacts of pandemic on the urban water cycle were assessed.
- Data mining from sewers can be enabled by digitalisation of the water industry.
- Effectiveness of public health measures can be monitored in the aggregate in sewers.

GRAPHICAL ABSTRACT



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ABSTRACT

The ongoing COVID-19 pandemic is, undeniably, a substantial shock to our civilization which has revealed the value of public services that relate to public health. Ensuring a safe and reliable water supply and maintaining water sanitation has become ever more critical during the pandemic. For this reason, researchers and practitioners have promptly investigated the impact associated with the spread of SARS-CoV-2 on water treatment processes, focusing specifically on water disinfection. However, the COVID-19 pandemic impacts multiple aspects of the urban water sector besides those related to the engineering processes, including sanitary, economic, and social consequences which can have significant effects in the near future. Furthermore, this outbreak appears at a time when the water sector was already experiencing a fourth revolution, transitioning toward the digitalisation of the sector, which redefines the Water-Human-Data Nexus. In this contribution, a product of collaboration between academics and practitioners from water utilities, we delve into the multiple impacts that the pandemic is currently causing and their possible consequences in the future. We show how the digitalisation of the water sector can provide useful approaches and tools to help address the impact of the pandemic. We expect this discussion to contribute not only to current challenges, but also to the conceptualization of new projects and the broader task of ameliorating climate change.

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1. Introduction

The ongoing COVID-19 pandemic is causing severe stress to society, with direct implications for public health and public water services. The event has been labelled as the first modern pandemic (Gates, 2020) and likely the worst crisis of our generation (Harari, 2020). While strict measures have been put in place worldwide to protect public health and inhibit the spread of the virus, experts have continued to express caution about future SARS-CoV-2 outbreaks and their consequences (Cobey, 2020).

Water is an essential resource for society, especially during a pandemic during which hygiene plays a pivotal role in mitigating the spread of the disease. Therefore, it is of paramount importance to secure a safe and reliable water supply while ensuring the proper management of the urban water cycle. The COVID-19 pandemic occurred at a critical time for the water sector as it navigates through two ongoing transformations. In recent years, the water sector has been transitioning toward the so-called "fourth revolution" (Sedlak, 2014), which aims at a more rational and sustainable management of water resources. This transformation has been encountering and merging with the digital revolution (Garrido-Baserba et al., 2020) which combines the power of Big data analytics and Artificial Intelligence approaches to develop new functionalities in water management.

As seen in other societal sectors, the pandemic is likely to act as the catalyst in the transition to a more digitalised water sector. While digitalisation is already present in the water management sector (especially in "developed" countries), both the extent and characteristics of its consolidation will likely be accelerated. An estimated 80% and 50% of the water utilities in developed and developing countries, respectively, are expected to undergo a digital transition to some extent by 2025 (Woetzel et al., 2018).

In the sections below, we first analyse the impacts of COVID-19 in the stages of the urban water cycle, followed by a discussion of these impacts projected onto the economic, social, and sanitary layers of the urban water service in order to provide a systematic view of the potential effects of the pandemic. Then, we present our consideration of how the water sector is experiencing the transformation toward digitalisation, which, in combination with the COVID-19 pandemic, is significantly altering the Water-Human-Data Nexus. Finally, we suggest that the adaptation process to the COVID-19 pandemic provides a unique opportunity to develop the water sector which in turn can catalyse key preparation and innovation for combating the challenge of climate change.

2. Impacts on the water cycle

The water cycle is characterised by inherent complexity, variability, and uncertainty due to interlinked social, natural, and engineered subsystems (Dunn et al., 2017; Makropoulos and Savić, 2019). Any impact on any of the subsystems can stress or compromise the stability of the whole system. The COVID-19 pandemic is already affecting the water system on multiple fronts, especially due to the behavioural change at a societal level which has triggered public policies enacted to fight against the pandemic. The immediate impacts are caused by the partial economic standstill and the resulting changes in water demand and citizens' habits. However, as presented in Section 3, these impacts are expected to have further effects on the water system, posing a risk for the financial sustainability of water utilities and workplace (American Water Works Association, 2020). With this in mind, the expectation of the multiple impacts on different subsystems makes it urgent to develop measures to increase the resilience of the existing system and when considering new infrastructures. This section highlights some of the most pressing impacts of the COVID-19 pandemic in the urban water cycle (Fig. 1).

2.1. Source

The partial shutdown of world economies has resulted in widespread improvements in air quality and in the ecological status of water bodies all over the world (Yunus et al., 2020). Although the water quality of some surface water bodies may have experienced improvements, most of the drinking water is withdrawn from sources such as reservoirs or aquifers which have been far less impacted by behavioural changes associated with the pandemic. While the requirements to condition water resources to potable levels may not change significantly, there have been concerns about relaxing the environmental regulations in order to mitigate the economic crisis (Bond et al., 2020; Nature's editorial, 2020). On the other hand, the reduction of the total commercial and industrial activity, and hence their discharges, could compensate for that potential effect on receiving water bodies as the daily mass loads could remain unaltered or decrease temporarily. If these impacted water bodies were also a potable source, treatment could become more costly.

2.2. Drinking water treatment and distribution

Although SARS-CoV-2 has not been detected in drinking water, and both academia and water practitioners agree that conventional water treatment methods using filtration and disinfection processes are capable of inactivating the virus (Maal-Bared et al., 2020; Naddeo and Liu, 2020), some public administrations are leaning toward an increase in the chlorine dose in drinking water during distribution due to fear or misinformation (Gonzalez, 2020; Tempest, 2020) or as additional preventive measure (Nghiem et al., 2020). Increased chlorination is likely to result in the further generation of Disinfection-By-Products (DBP) in addition to increased chemical costs at a time when utilities are facing shortfalls of funds. This potential increase coincides with changes in water consumption patterns, which challenge the operations to maintain the water quality in water storage tanks. Therefore, addressing such issues may require continuous monitoring and adjustment, as well as additional artificial intelligence (AI) support systems (Godo-Pla et al., 2019, 2020).

2.3. Use

The COVID-19 pandemic has changed social behaviour and consequently the water use patterns of society. While the cessation of non-essential services and some key economic sectors (especially industries and tourism) has led to a decline of the water demand worldwide (Table 1), the water use in residential areas has experienced a significant increase due to "stay at home" instructions. The shift of water demand from public places and workplaces to households has resulted in many utilities reporting peaks in water use between 2 and 4 hours later than in regular conditions (as a "perpetual weekend") (Berliner Wasserbetriebe, 2020; Eau de Paris, 2020; Hamburg Wasser, 2020).

2.4. Wastewater collection and treatment

The change in water use patterns also has a direct impact on wastewater collection and treatment. The overall decline in water demand is leading to an increase in wastewater concentration and decrease in the flow within the sewer system, with an associated reduction in velocity in the sewer and potential deposition of solids. The reduction in flow, and consequently flow velocity, may result in the accumulation of solids inside the sewer resulting in odours, corrosion, and the damage of conveyance equipment such as pumps. Reduction in the hydraulic loading rate and increase in concentration may result in operation outside the design criteria of a treatment plant. This would result in inefficient and possibly ineffective treatment.

Furthermore, a greater presence of flushable material in wastewater has been reported (EFE, 2020; Reviejo, 2020), especially toilet wipes

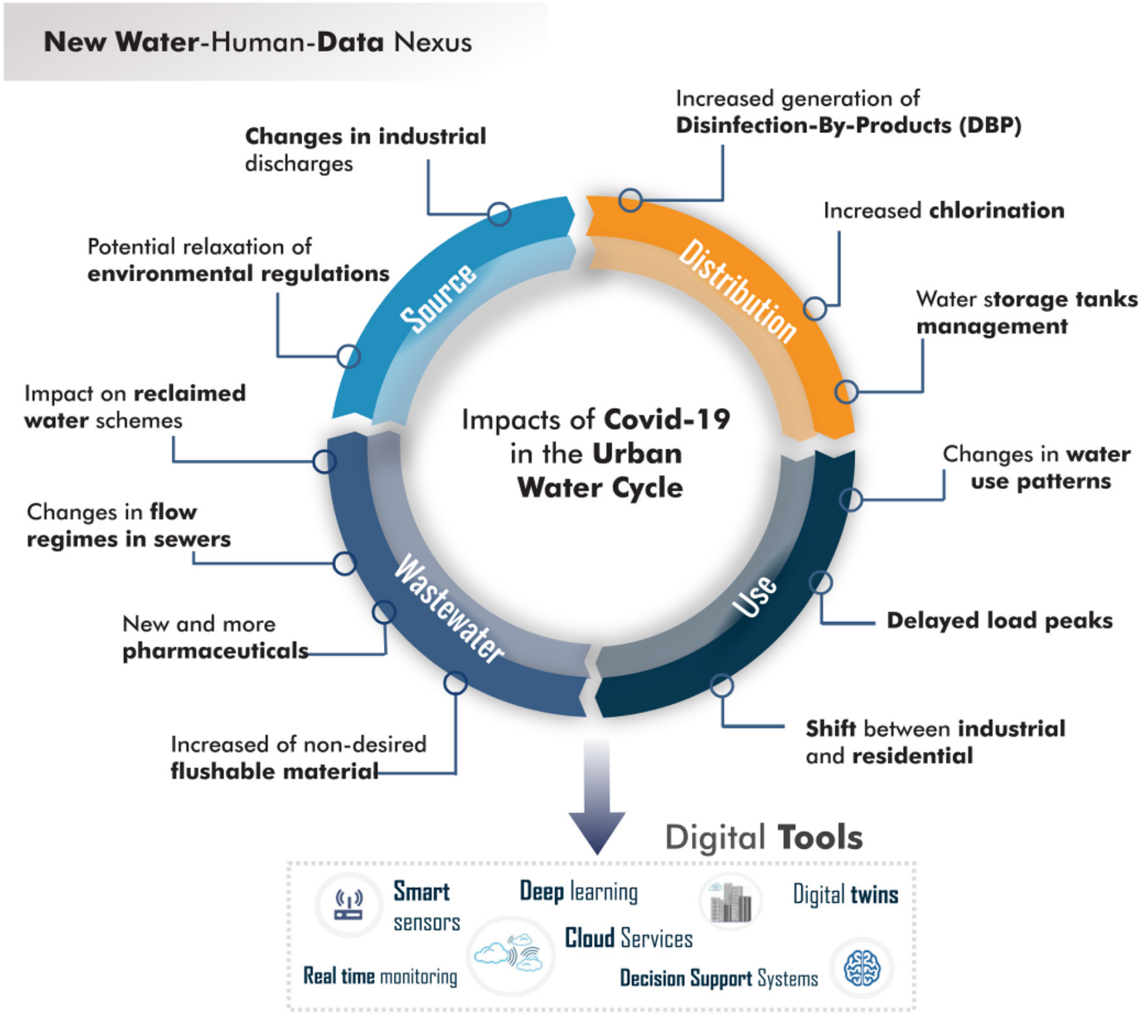

Fig. 1. Water revolution and digitalisation meet the COVID-19 pandemic.

Table 1
Water demand variation during the lockdown to reduce the spread of COVID-19.

Region	Global	Domestic	Industrial/commercial	Source:
Palma	−15%			(IB3, 2020)
Madrid	−7%	+3.5%		(Canal de Isabel II, 2020)
Barcelona	−(9.5%–11%)	+7%	−35%/50%	(xarxes, 2020)
Paris	−20%		−45%	(Eau de Paris, 2020)
Hamburg	+1%	+4%	−4%	(Hamburg Wasser, 2020)
Canada	−25%			(Webinar, 2020)
Colorado		+10%	−35%	(American Water Works Association, 2020)
Pittsburgh	−12%			(American Water Works Association, 2020)

(which has been a problem before COVID-19 pandemic) and protective masks. These materials contribute to the formation of large masses of solids that may clog the sewer systems and stall pumping stations (Kessler, 2016; Korilin, 2018).

Moreover, the pandemic has led to a significant increase in the demand of particular pharmaceutical products (e.g., anaesthetics, antibiotics, diuretics, etc.) (European Commission, 2020). Hence, wastewater is expected to contain a higher concentration of these products. Similarly, as the use of pharmaceutical products used to treat COVID-19 are becoming available (Dong et al., 2020), studies of their degradation throughout the wastewater collection and treatment cycle are needed to ensure the minimization of their harming potential before being discharged into water bodies (Wigginton and Boehm, 2020). As conventional treatment has proven ineffective for removing some pharmaceutical compounds (Soliman et al., 2007), changes in the treatment process and infrastructure (e.g., longer sludge retention time or tertiary operations) could be associated with increased cost, which would then be considered the premium value of the increased quality of the treated water.

Reduction in residential, commercial, and industrial consumption also results in the reduction of treated effluent that is used beneficially for sustaining receiving water ecosystems (some ecosystems are dependent on effluent discharge from treatment plants), groundwater recharge for potable reuse, and other uses such as landscape irrigation. As such, the beneficial uses of recycled water will be negatively impacted.

3. Impacts on the water sector

The complexity of the water system needs a deliberately interdisciplinary, socio-technical approach (Dunn et al., 2017; Makropoulos and Savić, 2019). The water system not only involves the water engineering processes, but also a social dimension (e.g., social needs and values such as equity, data privacy, and legal issues, etc.) that should be reflected in water management. Therefore, as the water sector is embracing the digital transformation, the boundaries between conventional engineering (focused on technical processes) and socio-technical management (focused on social behaviour and their consequences throughout the water system) are going to be blurred due to the functionalities enabled by data and computer science.

3.1. Impact on the financial sustainability of the water sector

The worldwide pandemic effects on GDP and unemployment rates due to the economic standstill (McKee and Stuckler, 2020) pose a serious threat to the financial sustainability of water services (American Water Works Association, 2020; Nghiem et al., 2020). Water tariff structures are based on the assumption that regular conditions are sufficiently stable, but the shift in commercial and industrial discharge can adversely impact the revenue model of water utilities.

In the context of economic stagnation, many large and small businesses, industries, and households may be unable to keep up with the payments regarding water services. Vulnerable households are at risk of water supply cut off, which in addition to essential daily functions, pose a threat to public health (e.g. preventing them from regular handwashing and thus contributing to spreading the virus). Because of this connection, many countries and states have enacted a policy that suspends shut offs during the pandemic (e.g. Spain, California). Some utilities are extending window times to pay billings with no interests or applying discounts. However, in other regions, citizens may lack access to a clean water supply even in developed countries (e.g., Flint, MI). In sum, the COVID-19 pandemic has resulted in decreased revenue from delivered water service in addition to the potential costly breakdowns as a consequence of inadequate user practices. In some cases, this reduction in revenue may be permanent due to the permanent closure of businesses or industries in a specific area.

3.2. Impact on the workplace

Water utilities must deal with two challenges simultaneously in the current situation. The first challenge concerns the fact that water supply and treatment is a critical essential public service, so individuals must work (partially in-place) despite the pandemic. Safe conditions and protective equipment for staff are required. Physical distancing and similar measures in the workplace may change work in water companies and the management of water plants (Eurofound, 2020). This situation can encourage the development of remote working and “digital twins” in order to control processes remotely, slowly replacing the retiring physical workforce with a more technologically adapted workforce or even partially through a “digital workforce” consisting of software tools. However, the irreplaceable experience of professionals who ultimately assume the responsibility of operations and error should not be forfeited for the sake of technological transition or cost since the workforce is only trained on fundamentals in school and field experience is an integrating component of formation (regardless of the technological disposition of the workforce elements). Also, the issue of professional responsibility and liability of digital support systems are not negligible and have already entered the discussion about the ownership of violations (i.e., the utility or the software provider), which is a common problem in autonomous AI systems (Anderson et al., 2014).

Social distancing established during the Covid-19 pandemic can foster the interaction between citizens and utilities through digital platforms. To do that, utilities need to further develop the user interface and the data management back-office (related to process operation). For instance, several utilities have closed their physical offices and now all the arrangements and operations must be performed digitally.

3.3. Sewage epidemiology and the role of Water Resource Recovery Facilities

The SARS-CoV-2 is shed in the faeces of COVID-19 patients, and the virus has been successfully detected in wastewater in many cities around world including the Netherlands (Medema et al., 2020), Australia (Ahmed et al., 2020), North-America (Peccia et al., 2020; Wurtzer et al., 2020), France (Wurtzer et al., 2020), Israel (Bar Or et al., 2020, p. 2), Italy (Rosa et al., 2020; Rimoldi et al., 2020), Spain (Randazzo et al., 2020; Balboa et al., 2020), and Turkey (Alpaslan Kocamemi et al., 2020). Although not much is known regarding the infectivity of the virus in the sewage and its direct threat to citizens, it confirms the potential key role of *Water Resource Recovery Facilities* (WWRF) in tracking and understanding the pandemic (Daughton, 2020) as well as future health emergencies.

Sewage epidemiology was first coined by using human wastewater to collect epidemiologic data on common drug products consumed and excreted into community sewage systems, and has since become a population-wide infectious disease surveillance tool featuring a proven track record for polio and the hepatitis A virus (Hart and Halden, 2020; Sims and Kasprzyk-Hordern, 2020). The capacity to track the SARS-CoV-2 in human sewage is being used to map the virus spread and the scale of community outbreaks (Hart and Halden, 2020). It has been suggested that an efficient monitoring of community wastewater influent to WWRFs could improve current prevalence estimations by detecting both symptomatic and asymptomatic cases (Lodder and Husman, 2020). Similarly, recent research points out that sewage-based coronavirus real-time monitoring could detect infection spikes up to 10 days earlier than with existing individual patient-based tests (UKCEH, 2020). Increasing the resolution of the actual impact COVID-19 in communities can not only help to implement faster and more effective measures, but it can also close the gap between tested and actual cases.

While monitoring wastewater effluents from hospitals can be a relevant source of information about the spread of the virus (Wang et al., 2020; Wu et al., 2020), they are not representative of the majority of the cases (not everyone needs to be hospitalized) plus hospitals are unlikely to have their own treatment system from where to obtain samples. Hospital sewage would only represent the portion of the cases that are known in the community, which have already been captured by the traditional epidemiology tracking system. Therefore, sewage tracking from pooled human samples taken in water-treatment plants serving a specific community is the best indicator to indicate the severity of the epidemic beyond those captured by the traditional epidemiological surveillance. Analysis of the viral genome sequence retrieved from human sewage could also serve as the tracking tool to trace the origin and evolution of the virus. The COVID-19 pandemic has elevated sewage to the status of a critical tool for human health monitoring.

4. Building the new digital tomorrow

With the digital revolution, especially the adoption of sensor systems and big data analytics, water has the potential to become one of society's most important sources of information. Interestingly, this information can be useful not only for optimizing technical processes, but also to better manage social systems by providing a real-time data source for behavioural guidelines and policy-making in a wide range of public values (e.g. public health, economy, etc.) (Corominas et al., 2018).

Digital technology is showing the capacity to extract the most intimate information from both individuals and communities about their state of health, genetics, nutrition habits, substance abuse, etc. from water and wastewater-related services (e.g., through smart metering, sewer mining, etc.) which can in turn blur the boundaries between water and public health services (Garrido-Baserba et al., 2020).

4.1. Water system process operation and re-design

The COVID-19 pandemic will not only change the daily operation of water infrastructure, but also the approach to upgrading and re-designing such infrastructure. To address the changes in water demand patterns, additional data sources may be needed to appropriately manage the resource, pushing the use of smart meters and sensors to be integrated within reliable models for the remote management of water flows while targeting optimal performance (Verdaguer et al., 2018).

In drinking water treatment plants and its distribution networks the adoption of digital solutions has hastened the development of advanced control systems using AI techniques. Such revolution can ensure regulatory compliance and increase the resilience of a facility for a changing environment with workforce optimisation (including decreasing the need for emergency call-outs). Prediction models, for example, can infer those network elements that are vulnerable to breakdowns. This also applies to leakage and fraud detection for addressing non-revenue water (Makropoulos and Savić, 2019).

Digital twins (DT) as a virtual replica of the physical assets or processes involved in urban water infrastructure (Fortune, 2019; Martínez et al., 2007) are used to remotely monitor the actual processes and apply AI techniques to conduct predictive maintenance of the assets, which enables the anticipation of possible failures and breakdowns, thus avoiding setbacks and production losses. In the water sector, DT are being used to manage water treatment processes and water networks (Martínez et al., 2007) and their capability to anticipate and simulate failure events. We can thus infer that in the future, DT will be used to further the automation of the water processes and enable real-time remote control of critical infrastructure under critical conditions (WaterWorld, 2020).

It is also important to consider how COVID-19 will accelerate the approach to new infrastructure design. We know that in a context of reduction economic resources, projection, execution, and maintenance of water infrastructures will be crucial. The information obtained from digital systems and its treatment by AI tools can provide useful insights. In this context, COVID-19 may modify the objective function used to allocate water infrastructures. Not only economic, but also social, environmental, and resilience aspects should be incorporated. In this context, AI tools and decision-support systems are essential and become critical investments where most necessary.

Digitalisation can also support the deployment of another management paradigm. Decentralised systems are more resilient, offer redundancy, and minimize personnel density and direct contact in the case of epidemics/pandemics (Garrido-Baserba et al., 2018; Sun et al., 2020). Digital platforms can support the management of infrastructure at the scale of a neighbourhood (Garrido-Baserba et al., 2020).

4.2. Economic and social

Digital tools can support the collection of invoices (thus, economic resources are available for the water utility to reinvest in infrastructure and management and thus cope with the crisis). This simplification of online payment processes thus conserves fiscal resources. Smart sensors and remote metering can help to reduce non-revenue water (e.g. leaks, fraud detection).

Furthermore, AI-backed systems may support new mechanisms to finance water infrastructure and management. For instance, in Barcelona there was an initiative before the COVID-19 pandemic to adapt environmental taxes (charged through the water bill) of urban districts according to their recycling rates (TOTBarcelona, 2019).

5. Water-Human-Data Nexus

Socio-technical systems, which include water systems, exist at the intersection between technology and the behavioural habits of ordinary people. Measures to cope with the pandemic include technological applications as well as an appropriate social behaviour in response to the needs of new demands and challenges (both staff and users). Digital services combined with data analysis and statistics can inform the effectiveness of a behavioural change guideline to overcome such unprecedented circumstances. As such, they would support a measure or deem it unnecessary if ineffective.

5.1. Confidence of the people in water services

Citizens want public services to be provided according to their values, their political preferences, and their ethical expectations (Moore, 1995). In the context of a crisis, citizens will be concerned with water utilities insofar as they relate to the quality of the services provided. Companies will need to confidently demonstrate the quality of water supplied and the quality of wastewater treatment. Machine learning tools may be useful to track public opinion on the quality of service. Clear, objective data should also be made available to educate the public on the process, process effectiveness and cost, and impacts associated with the treatment process.

The customer pressure to acquire more knowledge over the quality of their utilities is escalating. Currently individuals can monitor all home parameters, their energetic consumption in real time, and data on water quantity and quality from smart meters and sensors which may be the next information to be included in a home or phone management application. Furthermore, improving the social perception of water utilities could increase tap water consumption versus bottled water.

5.2. Value-based decision-making

In the context of digitalisation, new systems are going to be used to support decision-making concerning the management of both the social and technological elements of the water system. Usually management and public policy have to address “wicked problems” for which there are no unique solutions and therefore there have to reach social agreements (Grundmann, 2016). Thus, public decisions involve ethical dilemmas that present different desirable outcomes in which some public values are at conflict (Witesman and Walters, 2014). For instance, the policies to fight against the pandemic have posed a trade-off between protecting the public health and preserving the economy (McKee and Stuckler, 2020).

Although decision-making is supported by digital technologies, value judgments are still present. Many decision-making support systems are based on computational models that represent real phenomena which simplify and frame problems in a particular way, hence promoting some particular solutions over other alternatives (Aodha and Edmonds, 2017; Perello-Moragues et al., n.d.). However, decisions in the real-world can affect those aspects that were not included in the model (consciously or unconsciously).

Because digitalisation involves technologies that can provide more information to support decision-making in complex socio-technical problems, this leads inevitably to the need to clearly define the criteria and values beyond such decisions (Perello-Moragues and Noriega, 2020). For instance, if the virus is traced by sampling wastewater and this system is used to support lockdown de-escalation (i.e. policy-making), one should be transparent about the exact criteria and mechanisms (e.g., Multi-Criteria Decision Analysis) used to make such decisions in the context of this new information (that is, define the exact methodologies to perform the trade-off between the values involved).

AI can be used to build sandbox systems for policy simulation under different scenarios (Gilbert et al., 2018; Perello-Moragues et al., 2019). Simulation can be used to test policies or plans before their enactment in the real-world in order to anticipate their potential consequences and limitations, just as such simulation has been done for physical assets with digital twins. Digitalisation in the water sector can contribute to the further development of these methodologies to support decision-making in management and public policy. For instance, data from smart infrastructure (i.e. IoT-powered assets) can be used to build, calibrate, train, and validate computational models (Hu et al., 2017). As long as the assumptions, data, and limitations of a model are identified to policy makers, models can be a useful tool in the policy toolbox.

5.3. The importance of data and quality

The outcome of any model or data analysis is only as good as the data that are entered into the process. For example, digitalisation may be based on online sensor water quality data (Blumensaat et al., 2019; Vanrolleghem and Lee, 2003; Yuan et al., 2019). Inaccurate data due to sensor fouling, drift, or lack or maintenance or calibration can lead to erroneous results and consequently fallacious decisions (Rieger et al., 2010). Sewer systems especially are very harsh environments for sensors (Campisano et al., 2013). As such, utilities have to be vigilant to ensure the proper maintenance of sensors and other equipment in order to collect accurate data; statistical techniques are available for data quality verification (Corominas et al., 2018). The standardisation and accuracy of laboratory analytical techniques is also needed. For example, even though there are several international initiatives at this time (NORMAN network, JRC network), there is no standardised method for Covid-19 measurements. Laboratories use different methods, and some are more accurate than others. Even though sensor technology and biological and chemical analyses have grown significantly, there is still work to be done to ensure that accurate data are used.

Water utilities that address these new challenges by means of digitalisation would have to consider regulations on personal data in order to protect the privacy of citizens and companies. In regions where water utilities are subject to full disclosure through public records acts (e.g., United States Freedom of Information Act; 5 U.S.C. §552(a)(4)(F)), it would be challenging to protect private data, hence the need to rely on voluntary participation.

6. Re-building/thinking the future: climate change and new pandemics

The COVID-19 pandemic has revealed the necessity to re-think our society without delay in order to be prepared for future challenges such as climate change as well as other potential outbreaks. Accordingly, water systems must be further developed to accommodate such a total reimagining of infrastructure, digitalisation, and privacy protections.

Water management and water infrastructure design will require major changes to address climate change effects on the water cycle (e.g., extreme events) given that their assumptions may be "outdated" (e.g., alteration of precipitation return periods) (Barbara et al., 2015). Furthermore, climate change has impacts across many subsystems of the society (e.g., food, energy, etc.) which could lead to "unknown unknowns" in the water system. This unpredictability only highlights the necessity to develop new approaches to increase the capabilities of water management.

Digitalisation can provide tools and techniques to optimize management and develop new functionalities of water systems. For example, treatment plant automation, such as Variable Frequency Drives or enhanced aeration control, can result in significant aeration savings (Regmi et al., 2019). However, many scholars have pointed out that digitalisation may also have significant energy requirements, hence counterbalancing those savings from a global perspective (Vinuesa et al., 2020).

The digital revolution that has developed in recent years may be accelerated as a consequence of the COVID-19 outbreak. This response can be structured in three levels:

i. A technological level, by enabling an optimal adjustment of utilities' operations in the context of rapidly changing conditions. This level is achieved through the development of *digital twins* that integrate IoT and Big data analytics which can change the conceptualization of new infrastructures.
ii. An economic level, by contributing to the financial sustainability of water utilities supporting better asset, resource, and energy management.
iii. A water – human – data level to increase the confidence of citizens in water public services and warn the public and policy makers when signs of outbreaks or other challenging conditions (e.g. extensive drought) are shown.

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CRediT authorship contribution statement

Manel Poch: Conceptualization, Writing - original draft, Writing - review & editing, Supervision. **Manel Garrido-Baserba:** Conceptualization, Writing - review & editing, Visualization. **Lluís Corominas:** Writing - original draft, Writing - review & editing. **Antoni Perelló-Moragues:** Writing - original draft, Writing - review & editing. **Hector Monclús:** Writing - original draft, Writing - review & editing. **Manuel Cermerón-Romero:** Writing - original draft, Writing - review & editing. **Nikos Melitas:** Investigation, Writing - original draft, Writing - review & editing. **Sunny C. Jiang:** Investigation, Writing - original draft, Writing - review & editing. **Diego Rosso:** Writing - original draft, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Ahmed, W., Angel, N., Edson, J., Bibby, K., Bivins, A., O'Brien, J.W., Choi, P.M., Kitajima, M., Simpson, S.L., Li, J., Tscharke, B., Verhagen, R., Smith, W.J.M., Zaugg, J., Dierens, L., Hugenholtz, P., Thomas, K.V., Mueller, J.F., 2020. First confirmed detection of SARS-CoV-2 in untreated wastewater in Australia: a proof of concept for the wastewater surveillance of COVID-19 in the community. Sci. Total Environ. 728, 138764.

Alpaslan Kocamemi, B., Kurt, H., Hacioglu, S., Yarali, C., Saatci, A.M., Pakdemirli, B., 2020. First Data-Set on SARS-CoV-2 Detection for Istanbul Wastewaters in Turkey.

American Water Works Association, 2020. The Financial Impact of the COVID-19 Crisis on U.S. Drinking Water Utilities.

Anderson, J.M., Kalra, N., Stanley, K.D., Sorensen, P., Samaras, C., Oluwatola, O.A., 2014. Liability implications of autonomous vehicle technology. Autonomous Vehicle Technology. RAND Corporation; JSTOR, pp. 111–134.

Aodha, L. ní, Edmonds, B., 2017. Some pitfalls to beware when applying models to issues of policy relevance. In: Edmonds, B., Meyer, R. (Eds.), Simulating Social Complexity: A Handbook. Springer International Publishing, pp. 801–822.

Balboa, S., Mauricio-Iglesias, M., Rodríguez, S., Martínez-Lamas, L., Vasallo, F.J., Regueiro, B., Lema, J.M., 2020. The fate of SARS-CoV-2 in wastewater treatment plants points out the sludge line as a suitable spot for incidence monitoring. medRxiv.

Bar Or, I., Yaniv, K., Shagan, M., Ozer, E., Erster, O., Mendelson, E., Mannasse, B., Shirazi, R., Kramarsky-Winter, E., Nir, O., Abu-Ali, H., Ronen, Z., Rinott, E., Lewis, Y.E., Friedler, E.F., Paitan, Y., Bitkover, E., Berchenko, Y., Kushmaro, A., 2020. Regressing SARS-CoV-2 Sewage Measurements onto COVID-19 Burden in the Population: A Proof-of-Concept for Quantitative Environmental Surveillance.

Barbara, M., Lily, B., John, C., Karen, K., Mohammad, K., Kevin, L., Patricia, M., Emmanuel, N., Arka, P., John, P., Samuel, R., Cristiane, S., A., W.W., John, W., 2015. Progress and recommendations for advancing performance-based sustainable and resilient infrastructure design. J. Water Resour. Plan. Manag. 141 (12), A4015006.

Berliner Wasserbetriebe, 2020. Berlin schläft in der Krise länger. Twitter March 31. https://twitter.com/wasserbetriebe/status/1245092946908712961.

Blumensaat, F., Leitão, J.P., Ort, C., Rieckermann, J., Scheidegger, A., Vanrolleghem, P.A., Villez, K., 2019. How urban storm- and wastewater management prepares for emerging opportunities and threats: digital transformation, ubiquitous sensing, new data sources, and beyond—a horizon scan. Environ. Sci. Technol. 53 (15), 8488–8498.

Bond, A.J., Morrison-Saunders, A., Retief, F.P., Doelle, M., 2020. Environmental Regulations Likely to be First Casualties in Post-pandemic Recovery. The Conversation May 14. http://theconversation.com/environmental-regulations-likely-to-be-first-casualties-in-post-pandemic-recovery-137941.

Campisano, A., Cabot Ple, J., Muschalla, D., Pleau, M., Vanrolleghem, P.A., 2013. Potential and limitations of modern equipment for real time control of urban wastewater systems. Urban Water J. 10 (5), 300–311.

Canal de Isabel II, 2020. The use of dishwashers, taps and cisterns increased between 6% and 19% during lockdown. https://www.canaldeisabelsegunda.es/en/-/consumo-agua-confinamiento.

Cobey, S., 2020. Modeling infectious disease dynamics. Science 368 (6492), 713–714.

Corominas, Ll, Garrido-Baserba, M., Villez, K., Olsson, G., Cortés, U., Poch, M., 2018. Transforming data into knowledge for improved wastewater treatment operation: a critical review of techniques. Environ. Model. Softw. 106, 89–103.

Daughton, C., 2020. The international imperative to rapidly and inexpensively monitor community-wide Covid-19 infection status and trends. Sci. Total Environ. 726, 138149.

Dong, L., Hu, S., Gao, J., 2020. Discovering drugs to treat coronavirus disease 2019 (COVID-19). Drug Discov. Ther. 14 (1), 58–60.

Dunn, G., Brown, R.R., Bos, J.J., Bakker, K., 2017. Standing on the shoulders of giants: understanding changes in urban water practice through the lens of complexity science. Urban Water J. 14 (7), 758–767.

Eau de Paris, 2020. Confinement: Ce que notre consommation d'eau nous dit de Paris. October 4. http://eaudeparis.fr/nc/lespace-culture/actualites/actualite/news/confinement-ce-que-notre-consommation-deau-nous-dit-de-paris/.

EFE, 2020. La depuradora de A Coruña confirma la presencia del virus en las aguas residuales. eldiario.es. April 5. https://www.eldiario.es/sociedad/depuradora-Coruna-confirma-presencia-residuales_0_1023648048.html.

Eurofound, 2020. COVID-19 Could Permanently Change Teleworking in Europe. Eurofound March 26. https://www.eurofound.europa.eu/news/news-articles/covid-19-could-permanently-change-teleworking-in-europe.

European Commission, 2020. Guidelines on the optimal and rational supply of medicines to avoid shortages during the COVID-19 outbreak. https://ec.europa.eu/health/sites/health/files/human-use/docs/guidelines_isc_en.pdf.

Fortune, D., 2019. The digital twin in water infrastructure. Innovyze. February 27. https://www.innovyze.com/en-us/blog/the-digital-twin-in-water-infrastructure/.

Garrido-Baserba, M., Vinardell, S., Molinos-Senante, M., Rosso, D., Poch, M., 2018. The economics of wastewater treatment decentralization: a techno-economic evaluation. Environ. Sci. Technol. 52 (15), 8965–8976.

Garrido-Baserba, M., Corominas, L., Cortés, U., Rosso, D., Poch, M., 2020. The fourth-revolution in the water sector encounters the digital revolution. Environ. Sci. Technol. 54 (8), 4698–4705.

Gates, B., 2020. The First Modern Pandemic. Gatesnotes.Com April 23. https://www.gatesnotes.com/Health/Pandemic-Innovation.

Gilbert, N., Ahrweiler, P., Barbrook-Johnson, P., Narasimhan, K.P., Wilkinson, H., 2018. Computational modelling of public policy: reflections on practice. J. Artif. Soc. Soc. Simul. 21 (1), 14.

Godo-Pla, L., Emiliano, P., Valero, F., Poch, M., Sin, G., Monclús, H., 2019. Predicting the oxidant demand in full-scale drinking water treatment using an artificial neural network: uncertainty and sensitivity analysis. Process Saf. Environ. Prot. 125, 317–327.

Godo-Pla, L., Emiliano, P., González, S., Poch, M., Valero, F., Monclús, H., 2020. Implementation of an environmental decision support system for controlling the pre-oxidation step at a full-scale drinking water treatment plant. Water Sci. Technol. 81 (8), 1778–1785.

Gonzalez, M., 2020. Emaya aumenta la cantidad de cloro en el agua del grifo por recomendación de la OMS. Última Hora. March 29. https://www.ultimahora.es/noticias/local/2020/03/29/1152509/coronavirus-mallorca-emaya-aumenta-calor-agua.html.

Grundmann, R., 2016. Climate change as a wicked social problem. Nat. Geosci. 9 (8), 562–563.

Hamburg Wasser, 2020. Schlafen Menschen in Hamburg in Zeiten der Krise länger?. June 4. https://www.hamburgwasser.de/privatkunden/unternehmen/presse/schlafen-menschen-in-hamburg-in-zeiten-der-krise-laenger/

Harari, Y.N., 2020. The World After Coronavirus. Financial Times March 20. https://www.ft.com/content/19d90308-6858-11ea-a3c9-1fe6fedcca75.

Hart, O.E., Halden, R.U., 2020. Computational analysis of SARS-CoV-2/COVID-19 surveillance by wastewater-based epidemiology locally and globally: feasibility, economy, opportunities and challenges. Sci. Total Environ. 730, 138875.

Hu, Y., Quinn, C.J., Cai, X., Garfinkle, N.W., 2017. Combining human and machine intelligence to derive agents' behavioral rules for groundwater irrigation. Adv. Water Resour. 109, 29–40.

IB3, 2020. El consum d'aigua es redueix durant el confinament. Retrieved 30 June 2020, from. https://ib3.org/el-consum-daigua-es-redueix-durant-el-confinament.

Kessler, M., 2016. Are Wet Wipes Wrecking the World's Sewers? The Atlantic October 14. https://www.theatlantic.com/science/archive/2016/10/are-wet-wipes-wrecking-the-worlds-sewers/504098/

Korilin, K., 2018. 'Flushable' Wet Wipes Cause Major Sewage Blockages in UK. CNN November 13. https://www.cnn.com/2018/11/13/uk/flushable-wet-wipes-gbr-scli-intl/index.html.

Lodder, W., Husman, A.M. de R., 2020. SARS-CoV-2 in wastewater: potential health risk, but also data source. Lancet Gastroenterol. Hepatol. 5 (6), 533–534.

Maal-Bared, R., Munakata, N., Bibby, K., Brisolara, K., Gerba, C., Sobsey, M., Schaefer, S., Swift, J., Gary, L., Sherchan, S., Babatola, A., Olabode, L., Reimers, R., Rubin, A., 2020. Coronavirus and Water Systems. Water Environment Federation December 5. http://wef.org/news-hub/wef-news/coronavirus-and-water-systems/.

Makropoulos, C., Savić, D.A., 2019. Urban hydroinformatics: past, present and future. Water 11 (10), 1959.

Martínez, F., Hernández, V., Alonso, J.M., Rao, Z., Alvisi, S., 2007. Optimizing the operation of the Valencia water-distribution network. J. Hydroinf. 9 (1), 65–78.

McKee, M., Stuckler, D., 2020. If the world fails to protect the economy, COVID-19 will damage health not just now but also in the future. Nat. Med. 26 (5), 640–642.

Medema, G., Heijnen, L., Elsinga, G., Italiaander, R., Brouwer, A., 2020. Presence of SARS-coronavirus-2 RNA in sewage and correlation with reported COVID-19 prevalence in the early stage of the epidemic in the Netherlands. Environ. Sci. Technol. Lett. 7 (7), 511–517 (acs.estlett.0c00357).

Moore, M.H., 1995. Creating Public Value: Strategic Management in Government. Harvard university press.

Naddeo, V., Liu, H., 2020. Editorial perspectives: 2019 novel coronavirus (SARS-CoV-2): what is its fate in urban water cycle and how can the water research community respond? Environ. Sci. Water Res. Technol. 6 (5), 1213–1216.

Nature"s editorial, 2020. The sustained undermining of science by the EPA's leaders is a travesty. Nature 581 (7806), 7–8. https://doi.org/10.1038/d41586-020-01310-y.

Nghiem, L.D., Morgan, B., Donner, E., Short, M.D., 2020. The COVID-19 pandemic: considerations for the waste and wastewater services sector. Case Stud. Chem. Environ. Eng. https://doi.org/10.1016/j.cscee.2020.100006 Published online 2020 Apr 30.

Peccia, J., Zulli, A., Brackney, D.E., Grubaugh, N.D., Kaplan, E.H., Casanovas-Massana, A., Ko, A.I., Malik, A.A., Wang, D., Wang, M., Weinberger, D.M., Omer, S.B., 2020. SARS-CoV-2 RNA Concentrations in Primary Municipal Sewage Sludge as a Leading Indicator of COVID-19 Outbreak Dynamics (MedRxiv, 2020.05.19.20105999).

Perello-Moragues, A., Noriega, P., 2020. Using agent-based simulation to understand the role of values in policy-making. In: Verhagen, H., Borit, M., Bravo, G., Wijermans, N. (Eds.), Advances in Social Simulation. Springer International Publishing, pp. 355–369.

Perello-Moragues, A., Noriega, P., Poch, M., 2019. Modelling contingent technology adoption in farming irrigation communities. J. Artif. Soc. Soc. Simul. 22 (4), 1.

Perello-Moragues, A., Noriega, P., Popartan, A., & Poch, M. (n.d.) (in press). On three ethical aspects involved in using agent-based social simulation for policy-making. In P. Ahrweiler (Ed.), Advances in Social Simulation – Proceedings of the Social Simulation Conference 2019. Springer.

Randazzo, W., Truchado, P., Cuevas-Ferrando, E., Simón, P., Allende, A., Sánchez, G., 2020. SARS-CoV-2 RNA in wastewater anticipated COVID-19 occurrence in a low prevalence area. Water Res. 181, 115942.

Regmi, P., Stewart, H., Amerlinck, Y., Arnell, M., García, P.J., Johnson, B., Maere, T., Miletić, I., Miller, M., Rieger, L., Samstag, R., Santoro, D., Schraa, O., Snowling, S., Takács, I., Torfs, E., van Loosdrecht, M.C.M., Vanrolleghem, P.A., Villez, K., ... Rosso, D., 2019. The future of WRRF modelling – outlook and challenges. Water Science and Technology 79 (1), 3–14.

Reviejo, S., 2020. Crecen un 7% los atascos por toallitas húmedas que causan un gasto de 120 millones a las abastecedoras de agua. Público. December 5. http://www.publico.es/sociedad/toallitas-crecen-7-atascos-toallitas-humedas-causan-gasto-120-millones-abastecedoras-agua.html.

Rieger, L., Takács, I., Villez, K., Siegrist, H., Lessard, P., Vanrolleghem, P.A., Comeau, Y., 2010. Data reconciliation for wastewater treatment plant simulation studies-planning for high-quality data and typical sources of errors. Water Environ. Res. 82 (5), 426–433.

Rimoldi, S.G., Stefani, F., Gigantiello, A., Polesello, S., Comandatore, F., Mileto, D., Maresca, M., Longobardi, C., Mancon, A., Romeri, F., Pagani, C., 2020. Presence and vitality of SARS-CoV-2 virus in wastewaters and rivers. medRxiv.

Rosa, G.L., Iaconelli, M., Mancini, P., Ferraro, G.B., Veneri, C., Bonadonna, L., Lucentini, L., Suffredini, E., 2020. First Detection of SARS_COV-2 in Untreated Wastewaters in Italy.

Sedlak, D., 2014. Water 4.0: The Past, Present, and Future of the World's Most Vital Resource. Yale University Press.

Sims, N., Kasprzyk-Hordern, B., 2020. Future perspectives of wastewater-based epidemiology: monitoring infectious disease spread and resistance to the community level. Environ. Int. https://doi.org/10.1016/j.envint.2020.105689 Available online 4 April 2020.

Soliman, M.A., Pedersen, J.A., Park, H., Castaneda-Jimenez, A., Stenstrom, M.K., Suffet, I.H.M., 2007. Human pharmaceuticals, antioxidants, and plasticizers in wastewater treatment plant and water reclamation plant effluents. Water Environ. Res. 79 (2), 156–167.

Sun, Y., Garrido-Baserba, M., Molinos-Senante, M., Donikian, N.A., Poch, M., Rosso, D., 2020. A composite indicator approach to assess the sustainability and resilience of wastewater management alternatives. Sci. Total Environ. 725, 138286.

Tempest, O., 2020. Tap Water in France Under Strict Surveillance [Text]. Smart Water Magazine April 15. https://smartwatermagazine.com/news/smart-water-magazine/tap-water-france-under-strict-surveillance.

TOTBarcelona, 2019. Barcelona anuncia una nova taxa de recollida d'escombraries. September 12. Tot Barcelonahttps://www.totbarcelona.cat/societat/barcelona-introdueix-cop-taxa-residus-225-425-euros-llar_2103848102.html.

UKCEH, 2020. Coronavirus: Testing Sewage an 'Easy Win' - Work Begins on UK System for Estimating COVID-19 Cases From Wastewater. UK Centre for Ecology & Hydrology https://www.bbc.com/news/science-environment-53257101.

Vanrolleghem, P.A., Lee, D.S., 2003. On-line monitoring equipment for wastewater treatment processes: state of the art. Water Sci. Technol. 47 (2), 1–34.

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. Sci. Total Environ. 624, 1308–1315.

Vinuesa, R., Azizpour, H., Leite, I., Balaam, M., Dignum, V., Domisch, S., Felländer, A., Langhans, S.D., Tegmark, M., Fuso Nerini, F., 2020. The role of artificial intelligence in achieving the Sustainable Development Goals. Nat. Commun. 11 (1), 1–10.

Wang, J., Shen, J., Ye, D., Yan, X., Zhang, Y., Yang, W., Li, X., Wang, J., Zhang, L., Pan, L., 2020. Disinfection technology of hospital wastes and wastewater: suggestions for disinfection strategy during coronavirus disease 2019 (COVID-19) pandemic in China. Environ. Pollut. 114665.

WaterWorld, 2020. Digital twins for managing water infrastructure. January 4. https://www.waterworld.com/water-utility-management/smart-water-utility/article/14173219/digital-twins-for-managing-water-infrastructure.

Webinar, O., 2020. Navigating Through the Financial Impact of Covid-19.

Wigginton, K.R., Boehm, A.B., 2020. Environmental engineers and scientists have important roles to play in stemming outbreaks and pandemics caused by enveloped viruses. Environ. Sci. Technol. 54 (7), 3736–3739.

Witesman, E., Walters, L., 2014. Public service values: a new approach to the study of motivation in the public sphere. Public Adm. 92 (2), 375–405. https://doi.org/10.1111/padm.12000.

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. McKinsey Global Institute.

Wu, F., Xiao, A., Zhang, J., Gu, X., Lee, W.L., Kauffman, K., Hanage, W., Matus, M., Ghaeli, N., Endo, N., Duvallet, C., 2020. SARS-CoV-2 Titers in Wastewater Are Higher Than Expected From Clinically Confirmed Cases. medRxiv.

Wurtzer, S., Marechal, V., Mouchel, J.-M., Maday, Y., Teyssou, R., Richard, E., Almayrac, J.L., Moulin, L., 2020. Evaluation of Lockdown Impact on SARS-CoV-2 Dynamics Through Viral Genome Quantification in Paris Wastewaters (MedRxiv, 2020.04.12.20062679).

xarxes, 2020. La producció d'aigua potable al sistema Ter Llobregat durant el Covid-19 baixa a volums inferiors al d'un dia festiu. Agència Catalana de l'Aigua April 10. https://aigua.blog.gencat.cat/2020/04/10/la-produccio-daigua-potable-al-sistema-ter-llobregat-durant-el-covid-19-baixa-a-volums-inferiors-al-dun-dia-festiu/.

Yuan, Z., Olsson, G., Cardell-Oliver, R., van Schagen, K., Marchi, A., Deletic, A., Urich, C., Rauch, W., Liu, Y., Jiang, G., 2019. Sweating the assets – the role of instrumentation, control, and automation in urban water systems. Water Res. 155, 381–402.

Yunus, A.P., Masago, Y., Hijioka, Y., 2020. COVID-19 and surface water quality: improved lake water quality during the lockdown. Sci. Total Environ. 731, 139012.