the international
water association

Global Trends & Challenges

in Water Science, Research and Management

A compendium of hot topics and
features from IWA Specialist Groups

Third edition

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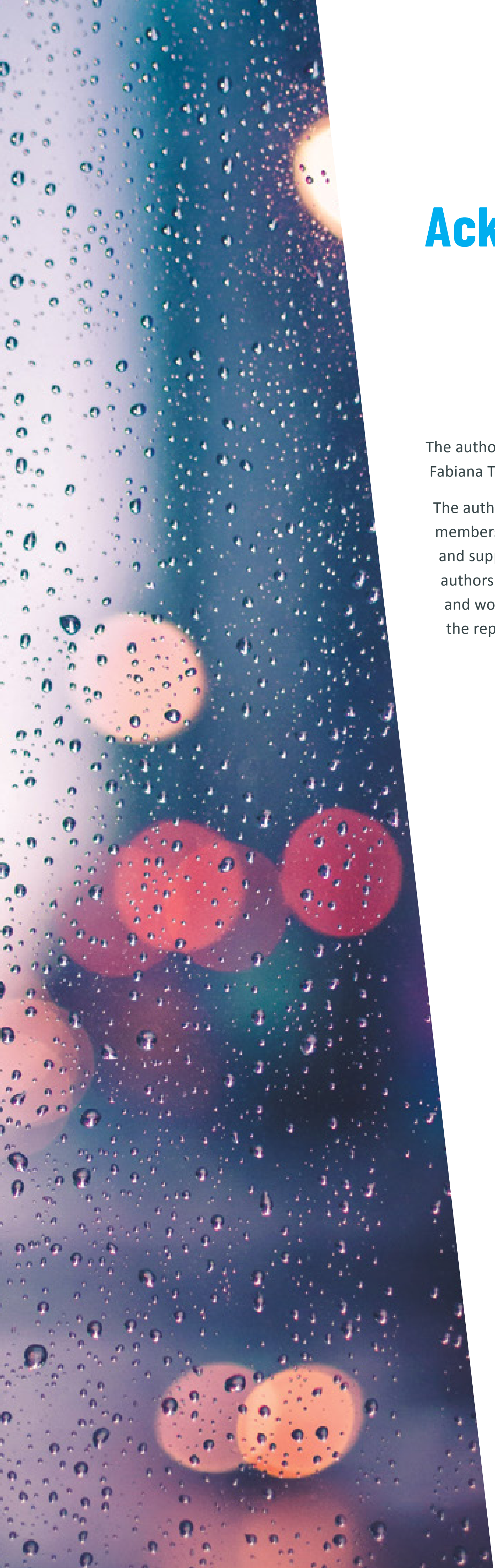

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Preface

The first two editions of the Global Trends and Challenges in Water Science, Research and Management (i.e., Global Trends Report) were published by The International Water Association (IWA) in 2012 and 2016, respectively, with the main aim of raising the profiles of the IWA Specialist Groups and visibility for expert members. The IWA Specialist Groups (http://www.iwa-network.org/iwa-specialist-groups/) are the core vehicle for IWA members networking and for issue-based interactions on water-related scientific, technical and management topics within IWA. Specialist Groups facilitate cooperation, networking and knowledge generation, primarily through regular conferences, meetings, working groups, task groups, newsletters and publications. They are created on a voluntary basis by IWA members and are strongly supported by the IWA office.

The 2012 edition included contributions from 25 Specialist Groups, the 2016 edition from 36 Specialist Groups and 2 Clusters. The reports drew upon the expertise of IWA's Specialist Groups who had identified hot topics, innovations and global trends in water science, research and management that have impact on solving global water challenges. A diversity of approaches was highlighted, from detailed technical and scientific aspects to more integrated ones.

We are happy to present here the Global Trend Report's third edition launched in September 2022 at the IWA World Water Congress & Exhibition in Copenhagen, Denmark. This edition is composed of three main themes:

I. Innovative Technologies;
II. Water and Health;
III. Resource Recovery and Circular Economy.

Within these themes, contributions from a total of 28 IWA Specialist Groups are gathered.

We invite you to discover the challenges, visions and trends of the wide variety of topics that IWA Specialist Groups cover. Enjoy!

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Innovative technologies

Reviewed by Professor Glen Daigger

| 1.1 |

Hydroinformatics

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Introduction and background

Hydroinformatics was established 30 years ago as a novel discipline in which computer modelling of water was combined with novel developments of Information and Communication Technologies for purposes of introducing novel cyber approaches to water engineering, management, and decision support.

From the beginning, hydroinformatics integrated knowledge from the social and technical domains to create so-called conjunctive knowledges, that are concerned with an understanding of how technical interventions have social consequences and how the resulting social changes in turn generate new technical developments (Voijnovic and Abbott, 2012). The social and technical nature of water problems arises from the complexity of interrelated phenomena and the large number of stakeholders and their diverse needs.

The evolution of research and innovation in hydroinformatics is well documented in the *Journal of Hydroinformatics* which is widely used by the international community for this purpose. In the last year, research in innovative technologies, methods and models focused on (a) new algorithms based on artificial intelligence, especially for real-time applications, (b) new sensors able to couple reliability and low costs and (c) new models able to take advantage of distributed computing or the increased computational capabilities of new processors. Fellini et al. (2019) developed an algorithm for real-time fault detection in the SCADA system of a modern water supply system (WSS) in an Italian alpine valley. By means of both hardware and analytical redundancy, the proposed algorithm compares data and isolates sensor faults through analysis of residuals. Mounce et al. (2019) described a novel genetic algorithm (GA) optimisation of the fuzzy logic (FL) membership functions (MFs) for the developed control algorithm. Johns et al. (2019) presented two engineering inspired hybrid evolutionary algorithms (EAs) for the multi-objective design of water distribution networks. Yang et al. (2019) proposed a framework supporting the acquisition of high-quality solutions and optimal reservoir operation decision-making based on improved multi-objective particle swarm optimisation (IMOPSO), a new efficient multiple-criteria decision making (MCDM) model based on TOPSIS and grey correlation analysis (GCA).

With the aim of developing new sensors and monitoring strategies, Shi et al. (2019) reported the use of a customised in-pipe fibre optic pressure sensor array for hydraulic transient wave separation and pipeline condition assessment. Sambito et al. (2019) proposed a new adaptive methodology to locate sensors in urban drainage systems, with the aim of avoiding illegal discharge of contaminants. Badillo-Olivera et al. (2019) proposed a new burst detection and location technique for pressurised pipelines based on an extension of the differential evolution (DE) algorithm.

In the field of new models, advanced analysis methods and computing strategies, Agliamzanov et al. (2019) presented a web-based volunteer computing framework for hydrological applications that requires only a web browser to participate in distributed computing projects. Simone et al. (2019) proposed the domain analysis of several real water distribution networks (WDNs) using edge betweenness in order to capture hydraulic behaviour based on network structure, namely for understanding the role of topological features in emergent hydraulic behaviour. Marquez-Calvo and Solomatine (2019) considered the problem of robust optimisation, and presented the technique called robust optimisation and probabilistic analysis of robustness (ROPAR). It has been developed for finding robust optimum solutions of a particular class in model-based multi-objective optimisation (MOO) problems (i.e., when the objective function is not known analytically) where some of the parameters or inputs to the model are assumed to be uncertain.

Innovative technologies in hydroinformatics

As Hydroinformatics is aimed at developing new methods and models based on technological advances, the following paragraphs will describe five relevant examples in which the availability of new technologies was used to solve problems or improve our understanding of water systems.

Automated detection of pipe bursts / leaks in water distribution networks

Water leakage is a major issue for water utilities worldwide. Despite all the past advances in developing different leak detection methods (Puust et al., 2010), there is still a need to improve the efficiency and reliability of these methods. Pressure and flow sensors are becoming increasingly more affordable, and many utilities have gone down the route of installing these sensors in water distribution networks. This forms the basis of the event recognition system (ERS) that was developed to detect pipe bursts/leaks but also other events such as various equipment failures. Sensor data are processed in near real-time, and bursts and other events are detected using the following key actions and related AI methods (Romano et al., 2014): (a) capturing and predicting the expected patterns of pressure/flow signals assuming that no event has occurred (done using artificial neural networks), (b) collecting evidence that an event has occurred by identifying discrepancies between predictions and incoming observations (done using statistical process control) and (c) inferring the probability that a burst / event has occurred in the pipe network (done using Bayesian networks). Alarms occur when detection probability becomes larger than some pre-specified threshold.

Elements of ERS, developed during a research project, were built into the commercial water network (ERWAN) system. ERWAN has been in use by a large UK water company since 2015. The system processes data from over 7,000 pressure sensors coming in every 15 minutes. ERWAN is able to detect bursts/leaks and other events in a timely and reliable manner. In addition to detection, ERWAN can proactively prevent burst events by detecting equipment failures that often precede these events. Note that ERWAN does not use a hydraulic or any other model of the water distribution network, hence it is very scalable. The use of ERWAN has resulted in multiple benefits for the water company, including major operational cost savings to date and reduced leakage. All this has led to improved customer service to over 7 million people.

Similar machine learning based methods have been developed for detection of discoloured water in water distribution systems (Meyers et al., 2015), prediction of combined sewer overflows (Rosin et al., 2018) and blockages (Bailey et al., 2016) in sewer systems, detection of water quality events at treatment works (Riss et al., 2018) and detection of sensor data anomalies (Branisavljevic et al., 2011).

AI-based asset condition assessment of sewers

CCTV surveys are the main method used for the inspection of sewers around the world. The video recordings are obtained by mounting a video camera on the pipe inspection gadget, a device that can move along the sewer in a controlled manner. Video recordings collected this way are then analysed by trained technicians, either *in situ* or in the office, with the aim of identifying and annotating various faults such as displaced joints, cracks, and debris, to name a few. This is a time-consuming process involving technicians watching hours of CCTV footage at a time. Unsurprisingly, this often leads to inconsistently annotated faults and may result in missing important structural faults that, in turn, could lead to serious flooding and/or pollution incidents.

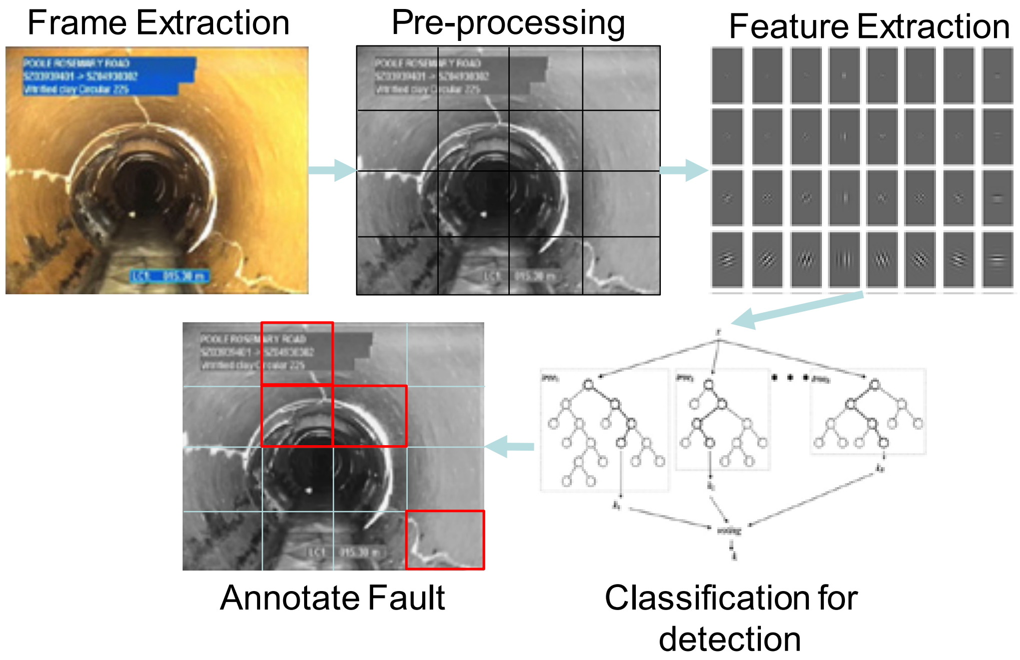
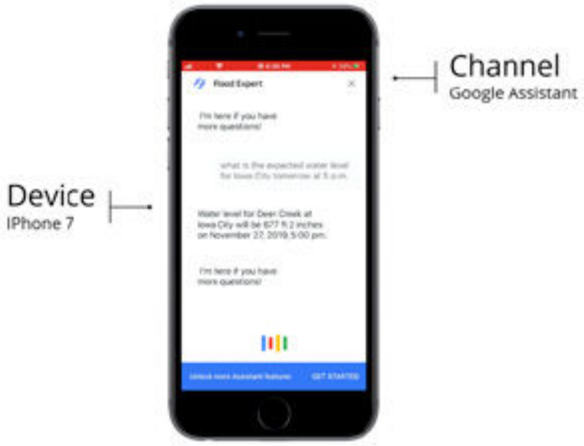


Figure 1.1 Principal steps of automated fault detection methodology: frame extraction, pre-processing, feature extraction, classification for detection, fault annotation.

The novel technology presented here (Figure 1.1) automates the process of detection and classification of sewer faults to a large extent (Myrans et al., 2018 and 2019). Still images are first sampled from the analysed CCTV video recording. Each image is then pre-processed, reducing it to a uniform resolution and converting from colour to greyscale. Feature extraction is then used to further simplify the image by calculating a pre-defined feature descriptor for the processed image. This is commonly a GIST descriptor, providing a high-level representation of important aspect of an image. However, histograms of oriented gradients (HOG) descriptors have been shown to be similarly effective. Once the analysed image is effectively converted into a sequence of numbers, machine-learning methods such as Random Forest are used to detect and classify faults in an image. The fault detection technology was successfully tested and validated on CCTV images from the UK, Finland and Australia. This technology is currently being commercialised via a collaboration between the University of Exeter (under the coordination of Prof. Zoran Kapelan), a UK water company and a technology development company.

Intelligent systems in the water sector

The ever-increasing ubiquity of environmental sensing devices leading to collection of dense spatiotemporal data by the water sector to monitor, analyse and communicate water-related challenges. Artificial intelligence (AI) provides many approaches and smart solutions for environmental knowledge generation and communication for effective utilisation of high-volume and multi-dimensional data by decision-makers and stakeholders. Intelligent virtual assistants allow instant knowledge generation out of curated data resources by allowing users to interact using natural language queries (Qiu et al., 2017). Intelligent assistants are powered by comprehensive domain ontologies to grasp the world dynamics and technical concepts, just like an actual human expert (Sermet and Demir, 2021). A leading initiative for a shared and consensual semantic web is the open knowledge network (OKN), which stakeholders can utilise to build intelligent frameworks with natural language interfaces.



I'm here if you have more questions!

what is the expected water level for Iowa City tomorrow at 5 p.m

Water level for Deer Creek at Iowa City will be 677 ft 2 inches on November 27, 2019, 5:00 pm.

I'm here if you have more questions!

Figure 1.2 The Flood Expert in action accessed via Google assistant

An innovative use case for intelligent systems in hydroinformatics is the Flood Expert (Sermet & Demir, 2018), an ontology-based knowledge engine that users can interact with in natural language to compute the direct answer to a given flood-related question from curated sources of information. Flood Expert, the result of a research collaboration lead by Prof. Ibrahim Demir, relies on information-centric ontologies (Sermet & Demir, 2019a) to comprehend the environmental and hydrological concepts and their relationships. The core of Flood Expert consists of a natural language processing module and an inference engine to identify intent and compute results. It can be integrated into various communication channels (Figure 1.2) including virtual personal assistants (e.g., Siri, Cortana, Google assistant), smart home devices (e.g. Google Home, Amazon Echo), messaging applications (e.g. Skype, Messenger, Slack), immersive devices, and web-based systems. Additionally, an open-source web component is available for effortless and safe integration of smart assistants (e.g., Flood Expert) into any web platform with an accessible and voice-enabled user interface.

Optimal positioning of sensors

In recent decades, the growth of mini- and micro-industry in urban areas has produced an increase in the frequency of xenobiotic polluting discharges in drainage systems. Such pollutants are usually characterised by low removal efficiencies in urban wastewater treatment plants, and they may have an acute or cumulative impact on the environment. In order to facilitate early detection and efficient containment of illicit intrusions, the present work aims to develop a decision-support approach for positioning the water quality sensors (Tapoglou et al., 2020). It is mainly based on the use of decision-making support based on a Bayesian decision network, which is one of the basic approaches used for machine learning. The approach is specifically looking at soluble conservative pollutants, such as metals. By using the Bayesian approach, new information, coming from the analysis, is incorporated in the approach allowing the operator to gain insight on the system once new contamination events are detected and identified. In this way, the approach is suitable for solving problems in which data are initially piecemeal and the operator plans to improve the monitoring strategy.

Two main components are required to solve this problem: (a) a calibrated model for hydraulic and water quality simulations in sewer systems, like many available on the market or as open-source applications, and (b) a Bayesian solver for likelihoods estimation and probability update. A Bayesian network (BN) is a graphical structure that allows us to represent an uncertain domain. The nodes represent a set of random variables from the domain. A set of directed arcs connects pairs of nodes that represent the direct dependencies between variables. There are at least three distinct forms of uncertainty which an intelligent system needs to cope with (a) ignorance, which is

Figure 1.3 Massa Lubrense network (Italy): the network is represented in the model with nodes (blue circles), pipes (black dots), pumping stations (green rectangles), and catchments (with black dots indicating their barycentres). The figure shows the best location for 12 sensors (yellow triangles) according to the methodology compared with the actual monitoring stations (red circles).

due to the incomplete knowledge of the process, (b) physical randomness or indeterminism, which is due to the incomplete understanding of its governing laws, and (c) vagueness, which is due to the ambiguous interpretation of process. The approach, developed by researchers guided by Prof. Gabriele Freni, is able to evaluate the uncertainty and consider it in the identification of the best location for sensors (Figure 1.3 shows and example in a real network in which sensors were located before the optimisation exercise). Data collected using the updated locations can subsequently be used to re-define the uncertainties and further refine sensor location.

Virtual and augmented reality in hydroscience education

Vast amounts of environmental, hydrological, and economic data present challenges to communicate and turn these data into actionable knowledge for water resources management and disaster planning. Traditional methods to visualise and interact with geospatial data do not suffice since the scattered nature of data resources and types allows the constitution of a big picture only when associations of events and actions are presented together. Virtual and augmented reality applications allow effective communication of massive environmental data with engaging visualisations and realistic simulations for hydrological planning and extreme event assessment (Bernhardt et al., 2019; Wang et al., 2019; Sermet and Demir, 2022). In combination with intelligent systems and artificial intelligence, these technologies enable next-generation environmental information systems for decision-making, training, and education. Immersive simulation

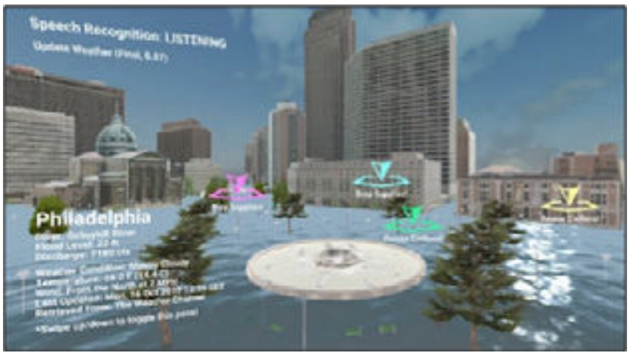


Figure 1.4 Flood action virtual reality game and training experience (above)

Figure 1.5 HoloFlood placed a hologram of the city on a conference room table (below) environments can support evaluation of disaster scenarios and water resources management strategies collaboratively from different physical locations and empower people to take part in the water cycle (e.g., pollution, consumption, distribution, policies) from a socio-hydrological perspective. They present the opportunity to examine the chain-reactions caused by extreme events and human intervention with advanced physics-based dynamics. First responders and maintenance staff can utilise these applications as a training tool to better prepare them for extreme events technically and psychologically.

Recent examples of augmented reality (AR) and virtual reality (VR) in hydroinformatics are flood action VR (Sermet & Demir, 2019b) and HoloFlood (Sermet & Demir, 2020), which are voice-enabled interactive applications for disaster preparedness and management powered by augmented and virtual reality. Flood action VR (Figure 1.4) is a 3D gaming environment, constructed with weather, disaster, and geographic data, which lets users to achieve certain tasks (e.g., escape, rescue, transportation) during a severe flood simulated for a real location. The application is equipped with Flood Expert for natural language interaction and information retrieval. HoloFlood (Figure 1.5) is a holographic decision support tool that simulates historical, current, or forecasted flood scenarios for a location as a hologram while providing property-specific economic damage estimations and vulnerable population. Both applications can be used by decision-makers, emergency responders, scientists, and stakeholders for increasing awareness, training personnel, educating public, and facilitate decision-making in a collaborative and reproducible manner.

The future outlook

New technologies both related to hardware and software are providing a significant input to research, allowing new solutions to old problems such as the mitigation of flooding, the maintenance of water systems, the location of leakage and contaminant intrusions. The availability of cheap and reliable sensors as well as the availability of higher computational resources allows the adoption of machine learning techniques that are pervading several sectors of industry and service provision. This trend will continue to change the water sector, giving managers a progressively more complete vision of their systems and allowing for immediate actions once operational conditions are not optimal. This new pervasive technology will produce smart sensors (including monitoring devices and analysis algorithms) able not only to provide reliable data but also complex judgement on the system performance.

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Trends in instrumentation, control and automation for the water industry

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Introduction to instrumentation, control and automation (ICA)

The ICA Specialist Group is an international forum to exchange knowledge, methodologies and experience on all aspects of ICA for water and wastewater systems. ICA aims to provide the monitoring, communication, data analytics, and control tools needed to cope with current and future technological innovations for the water and wastewater industries.

ICA is increasingly ubiquitous in the water industry. The technology is mostly hidden, and generally only emerges when its performance does not meet expectations. However, it can provide a whole new level of water utilities with higher capabilities, performance, resilience and reliability. The ultimate objectives of ICA are not only to keep the industry's assets running and to meet the product requirements, for example in terms of effluent quality, but also to do so efficiently and effectively, balancing investment and operational costs, robustness, quality and environmental care in an optimal operation using appropriate technology (IWA, 2016).

ICA has been a focus of the IWA and its predecessors since the 1970s (Olsson et al., 2014; Olsson, 2012). Early developments involved learning about the control of aeration processes, including the use of dissolved oxygen sensors. Since the 1970s, the ICA community has followed closely the challenges of the industry, including the development of instrumentation and control for nutrient removal and leak detection and location. Recent advances in the internet of things (IoT), digital transformation of the industry, and the expanded use of devices and applications are driving rapid change. With the exponential increase in data creation and availability, the potential and challenges associated with ICA are greater than ever.

Key terminology

What do we understand by ICA? Instrumentation ranges from simple monitoring sensors to complex online analysers. Control means either to bring a process from one status to another or maintain it at its set point. It can be achieved through single-loop controllers for the control of individual unit processes, or more advanced control systems based upon a combination of different control loops or by multi-variable controllers (Machado et al., 2009; Ostace et al., 2013). Automation includes signal analysis and cleansing, detection algorithms, operator support systems for decision (Poch et al., 2004), data communication from instruments to control system, control algorithms, plant simulation as a guide for the operator and, of course, a human-friendly interface and end user communication.

New terminology such as IoT, machine learning and smart networks has recently become popular in the field of ICA and has grown significantly during the last decade. IoT comprises the connection of physical things to the internet enabling data exchange, based on reasonably priced sensors and low-power consuming wireless telecommunication (i.e. the narrow-band IoT (NB-IoT), long range wide area network (LoRaWAN)). IoT is an emerging collection of technologies, and is expected to have a major impact on the future of ICA in urban water and wastewater systems (Yuan et al., 2019).

Machine learning (ML) is considered a subset of artificial intelligence (AI). Specifically, ML is a field of statistical research for training computational algorithms that split, sort and transform sets of data to maximise the ability to classify, predict, cluster or discover patterns (Reichstein et al., 2019). ML and intelligent or knowledge-based decision support systems are powerful tools to assist and support operators to determine the optimal operating conditions for existing water and wastewater systems. Applications such as digital twins are being used to help simultaneously predict the optimal design and operation of future and existing systems; and smart networks are being used to provide real-time data for various purposes.

Existing knowledge on ICA

ICA is currently applied throughout the urban and rural water systems at source water intakes, drinking water treatment plants (DWTPs), water distribution networks, sewer networks and water resource recovery facilities (WRRFs).

ICA in water supply systems

The use of control based on feedforward, feedback and predictive strategies in various DWTPs units enhances water quality and reduces operational costs. Typical loops include, for example, chemical dosing control for the coagulation and ultrafiltration processes and level and flow control. In water distribution systems, smart network technologies moving towards near-real-time control of pump operations have been widely researched and already implemented in full scale case-studies. Technologies such as ultrasonic and electromagnetic flow meters, as well as flow meters that can be inserted directly into a pipe are widespread today, while new developments have appeared around non-contact area velocity flowmeters. Leak detection using permanent sensor networks is a promising approach that has been applied in several large cities, but there are open research areas for optimisation. There has been significant progress in the detection, validation, and response to water quality anomalies in water systems by the US EPA surveillance and response (SRS) programs. SRS programs integrate multiple disparate data streams, such as customer complaints, online water quality monitoring, public health, security breaches, and strong business intelligence architecture to provide spatial recognition and validation of system problems.

Finally, there has been progressive innovation in sensor technology in the interaction with the devices including near-field communication (NFC) and bluetooth and the use of mobile phone applications to interact. There has also been the eventual development of highway addressable remote transducer (HART) communication as a primary verification tool.

ICA in sewers and WRRFs

ICA has been applied to sewer networks and WRRFs, from the hydraulic process to biological and chemical treatment processes. The technologies range from conventional control systems, that are typically unit-process oriented, to the increasing trend of control systems that consider multiple units in the plant to achieve plant-wide control and, in some cases, to control the entire wastewater system comprising sewers and treatment plants. The control aim is to enhance treatment performance leading to improved effluent quality and reduced energy and chemical consumption.

Combined sewer agencies are integrating multiple sensors for flow, level, weather with data analytics and visualisation tools to provide insights to reduce the amount of combined sewer overflows (CSOs) discharged into the environment. Water quality sensors are used in conjunction with sewer models and data analytics to provide insight into pollutants discharged into the collection system that can be harmful to downstream treatment facilities. This information is being used to identify the illegal discharger, and also to divert flows prior to treatment.

The use of ICA for improving the capacity of wastewater systems to handle increased loading has also attracted considerable attention in the past decade. With the concomitant computational and instrumentation improvements there is an interesting trend towards smart sensors with multiple detectors and transmission abilities, which can be placed anywhere in the process. Integrated control is now being achieved in full-scale applications and research methods to make them “smart” are being reported. The paradigm shift to resource recovery is also leading to the development of novel processes. WRRFs can increase substantially their complexity, with strong interactions among different process units, which both pose challenges and opportunities for ICA.

General trends and challenges

A recent survey of ICA Specialist Group members has shown the range of topics of interest to its members (Figure 1.6). Many of these hot topics are interconnected and, inevitably, emerge during deep discussions of other topics. Among them, the top five have been selected to be presented.

Machine learning techniques and artificial intelligence

The breakthrough in image classification obtained with deep learning methods in 2012 sparked a large-scale and renewed interest on ML techniques for learning from data. ML is a wide branch of AI, including many methods and techniques. The produced data models, and the decisions based on them, have led to impressive results in cases where data is representative, reliable, and voluminous. Not surprisingly, this has also resulted in many small and large companies as well as research groups to evaluate the potential of such methods in the water sector. Many early results from this new wave of projects have been presented at recent events focused on digitalisation and automation. In all likelihood, the proportion of such contributions will continue to rise in number in the next few years. Key factors that will determine success beyond the proof-of-concept will include (a) well-organised and flexible data storage, (b) continued and increased access to cheap computation, and (c) skilled technicians, engineers, and managers to translate abstract concepts and methods into practical, valued, and timely solutions for the water sector, all while avoiding the development of data-based systems that are ill-defined, too costly to maintain, or fail to satisfy all stakeholders.

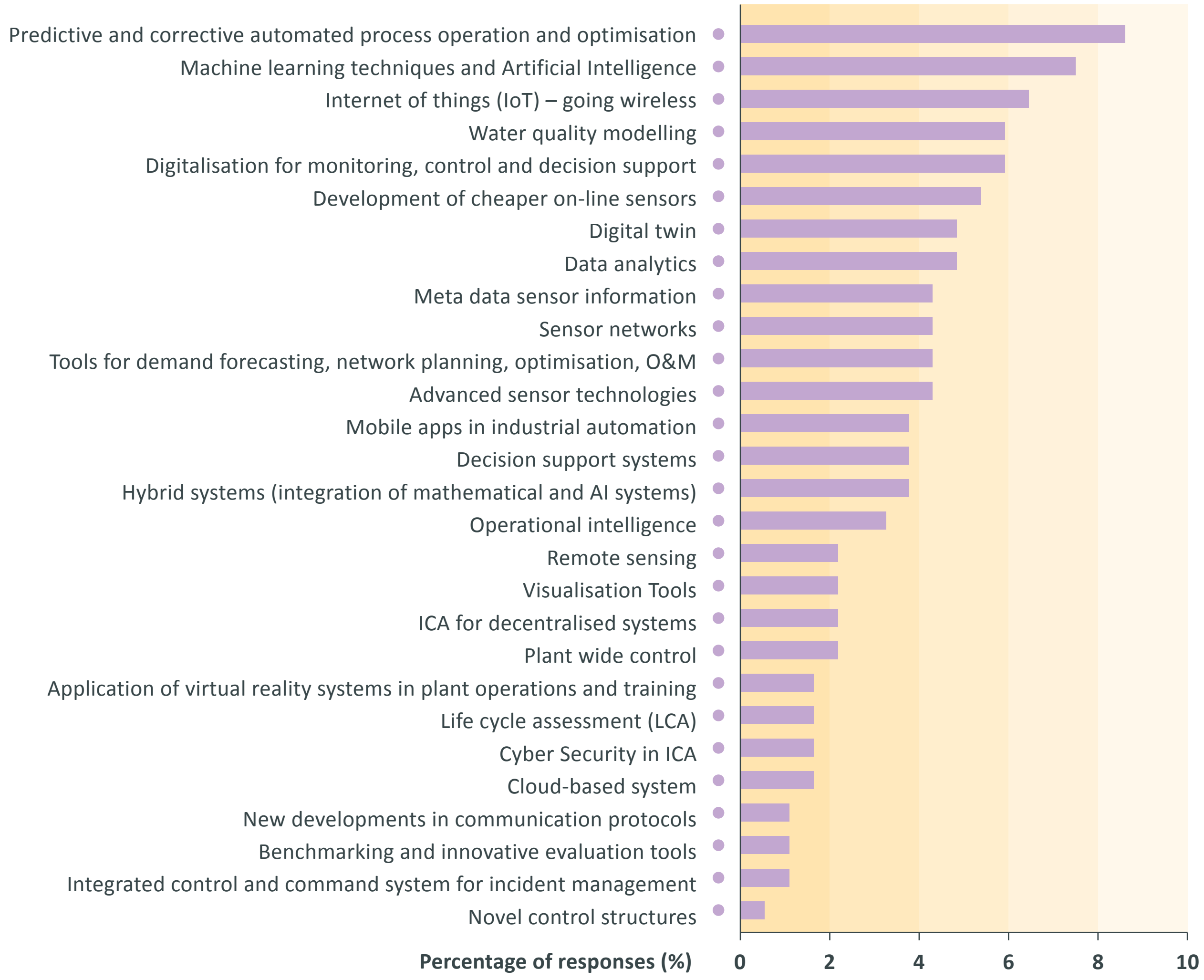

Figure 1.6 Survey results for selection of ICA topics

Predictive and corrective automated process operation and optimisation

Enhanced automated control and optimisation of existing facilities is required to move towards more energy-efficient and cost-effective processes. While corrective automated control is commercially available for individual unit processes, predictive supervisory systems applying modelling and benchmarking principles still require full-scale implementation and validation.

Regarding predictive automated control and optimisation, AI techniques appear as a powerful tool for solving environmental engineering problems. Predictive supervisory systems based on AI (e.g. artificial neural network, fuzzy logic, genetic programming, model trees, support vector machine, and particle swarm) support plant operators for increasing process reliability. Additionally, these approaches provide capabilities to address the complexities of uncertain, interactive and dynamic problems (Ye et al., 2020). Moreover, additional economic and environmental benefits may be derived from a tighter integration of both scheduling and predictive supervisory control for optimal decision-making. Traditional decision-making is hierarchical, based on multivariable supervisory control setting the set-points of the regulatory control layer over time horizons mainly depending on the response time of the process. Nevertheless, scheduling systems compute and implement operating decisions over different time horizons from days/weeks to the order of minutes/seconds. Hence, scheduling calculations provide targets not necessarily in the form of set-points for the supervisory layer (Baldea et al., 2014).

Communications within the water industry

Communications are changing rapidly with recent developments. The industry is moving towards its digital transformation, meaning that the amount of data is going to greatly stretch the bandwidth of communications networks. One of the common technologies nowadays is IoT, which is based upon the communication of data with a relatively low power, small amount of data and advantages and disadvantages depending on the application. Both NB-IoT and LoRaWAN are being used in smart meters and other IoT devices and are very successful. NB-IoT is applicable to the use of smart domestic water meters, as the data transfer needs are low, the range is high and the power use is low, meaning extended battery life decreasing maintenance costs.

This approach has been trialled by companies in the United Kingdom and is seen as a precursor for a much wider roll-out of smart water. LoRaWAN has been used on treatment works in wastewater systems to provide on-site communication where the bandwidth requirements do not discount the technology.

On the other hand, the advent of 5G mobile phone communications within the communications market means that data heavy industrial applications can utilise it, bringing the potential for the use of augmented reality (AR) and GIS mapping in field operations with the potential for remote assistance.

Water quality modelling

A key step in water quality management is data collection and processing. Monitoring is expensive and laborious and encompasses most of the water cycle, from WRRFs and CSOs, to rivers, lakes and the sea. Data has a geospatial and temporal component and includes flow and physicochemical parameters. It is also classified into sources, e.g. livestock and arable farming. Further challenges include biological sampling (e.g., faecal indicator organisms (FIOs)) and an increasing list of pollutants (i.e., plastics, perfluorooctane sulfonate (PFOS), perfluorooctanoic acid (PFO) and other micro-pollutants). Maintenance of equipment is resource-hungry. Flow meters in remote areas are prone to siltation and blockage. For other chemicals, such as FIOs, sampling campaigns only span bathing waters during summer.

Simulation is a complementary tool for management and decision making. In the UK, the source apportionment GIS (SAGIS) simulation environment is used to provide a breakdown of chemical inputs to rivers and lakes from the aforementioned sources (Comber et al., 2013). This is possible thanks to an extensive water quality monitoring database. However, simulations are only as good as the data collected. To handle uncertainty, each data point is associated to a degree of “trust”. When data are scarce, datasets are enhanced using different techniques, such as flow gauge hindcasting from runoff models and rainfall data.

Decision support systems (DSS)

DSS are defined as a computational system that helps decision makers in the process of deciding between alternatives or actions (Fox et al., 2000). Currently, most DSS are intelligent information systems able to integrate mathematical and statistical methods with AI techniques, geographic information systems and environmental ontologies. DSS can simultaneously manage numerical data and qualitative knowledge, as well as incorporate spatial and temporal dimensions. Thus, DSS are qualified tools to help reduce the time needed to make decisions in complex systems and improve their consistency and quality (Poch et al., 2004).

DSS are already a reality in the day-to-day operation of many water utilities and authorities all over the world. In the last decade, DSS has evolved from an academic concept and prototype to a real product able to solve present water management challenges. Current DSS include successful applications supporting different decision-making processes, from planning and design levels to advanced monitoring, control and optimisation of natural or urban water systems. In the coming years, DSS are expected to have an important role in the required new paradigm, i.e. going a step further, from circular water management towards healthier, more resilient and more just societies.

Challenges

Today, the water sector is investing intensively in the installation of large sensor networks along the urban and natural water cycle. This is largely inspired by the tremendous opportunities associated with learning from large and continuous sensor data streams and the advent of efficient computing hardware. There are, however, several challenges unique to the water sector that need to be addressed to continue to optimise and help these systems to mature such as the following:

1. Many variables that are key to process optimisation, e.g. microbial activity, cannot be measured directly today and must be inferred from the combination of domain knowledge and indirect measurements with tools such as soft-sensors. The development of robust hardware for measurement of variables of interest (e.g., micro-pollutants, microbial community composition and presence of invasive species) should also be prioritised. Another instrumentation challenge is the stringent discharge criteria for WRRFs, which pose a challenge when measuring, e.g., phosphorus and nitrogen at low concentrations.

2. Water presents a very harsh environment for electronic instruments, including pumps, valves and sensors. Hence, traditional design and optimisation has focused on robust hardware and operation, in turn leading to inflexible solutions with long payback periods and low resilience to climate change and strong population dynamics in urban environments. The development of efficient instrument maintenance plans will be critical for ICA to contribute, as expected, to the financial sustainability and resilience of urban water systems.

3. Currently, much of available data resides in isolated databases managed by distinct authorities. For example, it is typical that sewer and WRRF data are stored separately and in different formats. Additionally, utilities tend to process and gain value from only about 10% of the data they collect, due to lack of analytical tools and trained staff. Thus, effective data-based management requires that historically isolated data sources can be connected to each other. However, these connections must be executed in ways that protects privacy rights and safety-critical infrastructures from inadvertent malfunctions or cyber-criminal activities, while respecting ethical guidelines and standards.

4. As data become more abundant, new advanced digital tools are being developed to process it. It is paramount that industry organisations work with utilities, universities, and technology companies to allocate resources to create proper standards for maintenance and updates of these digital tools, i.e., source control, unit testing, and code documentation. The use of open architecture will allow this type of collaboration to be more successful, as opposed to proprietary systems that restrict the capabilities of external groups to make enhancements. Finally, there is currently a shortage of skilled data scientists and data engineers to carry out the collection and maintenance of water quality databases and digital tools, which should be a priority for universities to enhance their curricula.

Conclusions and research or development agenda

The move to an eventual digital transformation is starting within the industry at the current time, making the role of ICA increasingly important. The increasing amount of data is becoming a challenge to the industry. This brings with it challenges that the industry must face, including the need to develop new skill sets within the industry surrounding data and informational analytics.

Added to this are the challenges of identifying the technology available to address the issues faced by the water industry, i.e. matching technology to application. In terms of research and development and innovation within ICA, there are a number of areas that need to be addressed, including the following:

- What existing ICA technology does the water industry have to address the industrial challenge? Once these applications have been addressed, where is the gap within the technology available that will lead to research and development needs, and the development of novel sensor systems to address the gaps that exist?
- What communications gaps exist and how can the industry address them? There is the development of IoT and technologies such as NB-IoT and LoRaWAN, but these support specific applications. What other communications applications and challenges does the industry have and how can these be addressed?
- The industry is moving rapidly towards data visualisation and analytics techniques, but they need much further development. There is the expertise within the academic environment; however, this is not particularly proliferating into mainstream industry.
- Despite the move towards digital transformation, there are some basics within the industry that remain a problem, such as basic installation and maintenance techniques. This needs research and development of good practice within the industry, together with more effective use of ICA systems to realise the benefits.
- More research and development are needed on the practical aspects of ICA systems and how these systems can work effectively. For instance, there is an increased proliferation of sensor systems for visualisation of the collection network, but how these systems perform is currently not well known.

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| 1.3 |

Intermittent water supply: the challenge of improved level of service to customers

Authors: *Bambos Charalambous and Mohammed Shafei*
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Introduction

"It is relatively easy to turn a 24/7 system to an intermittent supply, but it is very hard to do the opposite."

The reality of intermittent water supply (IWS) has been evident in many countries, especially in low and middle income countries (LMIC). It has been estimated that only 52% of the world population has access to piped water on premises, of which 35% is affected by IWS, principally in LMIC countries (Laspidou and Spyropoulou, 2017, Kaminsky and Kumpel, 2018).

IWS leads to a self-feeding downward spiral (Charalambous and Laspidou, 2017) whereby increased urbanisation leads to higher water demand, which forces corresponding water network expansion. This is often carried out without guaranteed water production capacity. This reflects on the quality of service for consumers, encouraging the more privileged consumers to privately invest in supply augmentation, while the majority of the population is faced with insufficient and unreliable supply. These circumstances naturally result in low willingness to pay for the service and, therefore, reduce the income collected by water utilities. Moreover, the newly expanded networks are often executed without ensuring hydraulic integrity, and without applying the recommended design and operation standards. This will add to the direct effect of intermittent operation on the network infrastructure and cause the rapid deterioration of networks by accelerating the rate leaks occur, adding to the supply shortage, and adding to the capacity required to operate and maintain the failing networks. In the end, intermittent supply results in a deteriorating network, increased leakage, and higher non-revenue water.

Owing to this downward spiral, utilities are increasingly resorting to delivering intermittent supplies, often at fewer and shorter supply rotations. For water operators working in the midst of these conditions, the idea of recovering from IWS becomes a difficult target to hope or aim for. This presents the clear task of developing viable and effective approaches to water operators on how to take back control and reverse the downward spiral of IWS.

Definition of IWS

IWS is a course of action where the supply to parts of a water resource zone is cut off, usually in rotation, with the intention of preserving limited resources. This is an action that would be considered where the actual headroom, that is the difference between available supplies and demand within a water resource zone, is significantly less than the design headroom. Intermittent supply is not always managed and may occur when the service reservoir runs empty. The extent of IWS will depend on the degree of this deficit. IWS usually takes the form of rotating supply to different areas so that the restriction is suffered by all customers, though it is common to arrange for supply to critical customers, such as hospitals, to be maintained at all times. It is also frequent for areas to be shut off entirely. The repeated emptying and filling of the system causes severe problems with bursts, and thus leakage, because of pressure fluctuations every time the system is recharged. Thus, the action can be, to a certain extent, self-defeating. It is recommended that complete shut off is avoided if possible and that a minimum pressure is maintained in the system.

Existing knowledge on IWS

The hazardous effects of IWS have been well established through multiple sources of inference and from multiple disciplines.

Operational efficiency

The operation of networks under IWS leads to various operational problems that reduce the efficiency of water distribution and use, and on the side of both water utilities and consumers (Klingel, 2012; Totsuka et al., 2014). Contrary to the intention of extending water resources that drives utilities to initially attempt IWS, it has been recognised that IWS leads to greater quantities of water being lost. On the consumer side, and compared with continuous supply, water supply under IWS conditions leads to excessive consumption as stored water tends to be discarded by consumers when the new supply comes in. Additionally, private storage tanks often overflow and taps that are left open lead to uncontrolled water loss (Laspidou et al., 2017). On the utility side, the operation of IWS leads to ineffective supply and demand management, with inaccurate customer meters damaged by the frequent emptying and filling of the network and the subsequent vacuum and excessive air conditions in the pipe (Criminisi et al., 2009). Moreover, IWS results in inefficient operations, with direct financial burdens on the water utilities. This includes a decrease in revenue due to decreased water sales and willingness to pay, as well as additional expense for staff needed for frequently opening and closing valves and conducting the increased needed number of burst repairs (Jayaramu and Kumar, 2014).

Water quality and health

The operation of water networks under IWS is shown to create substantial health hazards due to the ingress of contamination through network breaks and backflows generated during the frequent network emptying events at the end of each supply regime (Kumpel and Nelson, 2014). The bacteriological water quality under an intermittent water supply regime has been shown to be substantially lower than that of a continuous service. Maintaining network pressure under continuous supply removes the risk of bacterial contamination in the distribution network. On the other hand, it is difficult to keep proper chlorination level in the network due to vastly varying hydraulic conditions with the repeated emptying and filling of the network, in addition to the frequent periods of high oxygenation aerobic bacteria have access to under IWS (Laspidou et al., 2017).

Asset longevity

The operation of the water network under IWS increases the rate of asset deterioration, and increased pipe bursts leading to higher leakage rates (Agathokleous and Christodoulou, 2016; Agathokleous et al., 2017). Water network topography and components are designed to operate under pressurised conditions. The sudden variation in flows and pressures under IWS, as well as the repeated dry and wet conditions, accelerate deterioration of the pipe network as well as water meters. Additionally, detecting and repairing leaks becomes exceedingly challenging as low and changing pressure render leak detection and control near impossible.

Societal cost

The operation of the water network under IWS means shorter and inconvenient supply times, and often means smaller available quantities. Consumers are therefore forced to search for alternative sources of water (Burt and Ray, 2014). In most cases, consumers pay high coping costs for additional facilities, such as private storage tanks, pumps, household treatment facilities, and water tanker purchases. This effect is experienced differently depending on consumer location. Consumers furthest away from supply points and those lying at higher elevations often receive less water than those nearer to the source and lying at lower elevations. Furthermore, those who cannot afford to pay the coping costs will have to travel sometimes long distances, and in the night, to public taps in order to secure small quantities of water (Laspidou et al., 2017).

General Trends

The last decade witnessed an increasing number of initiatives to tackle IWS within a wider scope of activities. The following is a summary of the main trends.

Roadmaps for transitioning from IWS to continuous water supply

Roadmaps for transitioning from IWS are a valuable tool for inspiring and guiding change. Roadmaps can be drawn to look at the wider scope of tackling water integrity at the sector level. Such roadmaps would focus on alternative and efficient water and energy resources, trunk main and storage capacity improvement, water use efficiency and consumer outreach and awareness, and tariff reform. Roadmaps can also be drawn to guide the detailed transition of distribution networks from IWS to continuous supply. Such roadmaps would focus on hydraulic optimisation, application of network control and monitoring technologies, assessment of water balances during transition, customer metering, and network inspection and maintenance (Charalambous et al., 2019).

Leveraging performance contracts

By setting increased supply time as a key project outcome, performance contracts in developing countries can focus on achieving an end to IWS. Customer surveys can help ensure the achievement; however, direct flow and pressure monitoring technologies can provide a cost-effective alternative. The same concept can be applied when public utilities receive direct funding for the purpose of service improvement, where the performance parameters can apply for the public utility instead of a private contractor.

Establishing demonstration areas of transitioning to continuous supply

To tackle the need for a change in mindsets, and demonstrate the possibility for transitioning from IWS, successful pilot areas can be a significant asset. Small pilot areas benefit from making small demands on the current state of supply while tackling a wide range of the technical and social challenges that would face a wider transition. Another benefit from successful pilot demonstrations is the analysis of the total water demand before and after transitioning, which can show reduction in some cases given sufficient demand management and leakage reduction or can otherwise provide more reliable figures on the true supply deficiency (Charalambous and Shafei, 2019).

Water loss assessment

There is a close link between intermittent supply and water loss. Pressure flux compromises the network's structural integrity. With IWS, pipe failures increase, meters malfunction, illegal connections spread, and the network deteriorates to the point where it is next to impossible to detect and fix leaks. That is when water contamination escalates to public health issues.

This has brought into attention the importance of validating performance indicators, especially water loss indicators, in terms of supply hours. The IWA Water Loss Specialist Group is recommending the use of "when system is pressurised", or w.s.p., indicators when reporting water loss indicators, including the infrastructure leakage index (ILI). This often shows a significant worsening of the measured performance when converted into average hours of system pressurisation and demonstrating the hidden effects of IWS on the system infrastructure.

Change of mindset

Ironically, IWS water often risks becoming contaminated and the cost in time often exceeds what wealthier consumers pay for water from house connections. Coping costs provide a lower bound to willingness-to-pay for water but are rarely quantified. Even those who argue that water should be provided free from public taps do not realise the significant economic costs in terms of time spent carrying water.

Still, it is possible to achieve continuous supply. The transition demands coordinated efforts by regulators, utilities, and consumers. It strongly requires a change of mind set by all concerned. Utilities must be willing to make changes in accountability to regain the social trust of consumers. Consumers, in turn, must agree to accept technical metering in exchange for a gradual increase in hours of supply. Metering allows financial recovery through tariff structures linked to performance incentives to save water, and governance reforms provide institutional backing for hard choices toward continuous supply. Throwing money at assets will fail. Education programmes targeting utilities and consumers, however, can demonstrate the benefits of a 24/7 service over coping and health costs.

From the top down, governments, donors and banks must oblige utilities to invest in water recovery as a prerequisite to receiving financial support or climate adaptation funds. *"If efficiency cannot be induced, it must be prescribed"*.

From the bottom up, staff must be trained and equipped to build capacity within utilities. *"Peer-to-peer learning helps build pride and a sense of professional purpose in a utility's technical staff"*.

Research development agenda

The emerging field of IWS management has to inform a multitude of disciplines about a growing area of inquiry that includes the following.

Developing a standard approach for transitioning from IWS to continuous supply

Developing a standard approach for transitioning from IWS to continuous supply is an ongoing process that tackles a critical challenge which remains largely unaddressed. Building on the presented methodology, the development of protocols, training programmes, and policy advocacy should follow for developing knowledge and expertise.

While transitioning from IWS through network rehabilitation and leakage reduction is the main current conceptual approach that applies universally, the evolution of demand patterns during and after the transition poses a human factor that cannot be predictably quantifiable. User demand behaviour may differ depending on water prices, provenance of unauthorised consumption, private storage, level of water conservation awareness, and many other local variables. Better guidelines and tools for planning and implementing the transition from IWS require more nuanced handling of complex aspects faced by the operators.

Understanding the physical effect of IWS

The downward spiral of IWS is intricately linked to efficient use of water resources. Yet, the detailed mechanism of how IWS leads to deteriorated network infrastructure and increased water loss is not well understood. A potential research venue is the long-term study of the relationship between measurable physical quantities, such as the pressure transient volume and frequency caused by filling and emptying of water networks, as well as quantifiable factors such as dry time and pipe material, and how they relate to the speed of deterioration using direct measurement of network transient volume at different locations within the same network and under different network topographies. The better understanding of this relationship can open the door to more nuanced approaches towards gradually alleviating the effects of IWS, even under conditions of severe water scarcity where IWS cannot be avoided.

Standardisation of hydraulic modelling of water networks under IWS

Hydraulic modelling is the main tool for designing water networks and analysing their behaviour. However, professional software packages available employ equations designed for pressurised networks (Ingeduld et al., 2008). Attempts at modelling network filling and emptying have been made at the academic level (De Marchis et al., 2011). Another approach is through the special treatment of currently available modelling engines (El Achi and Rouse, 2019). In either case, there is a lack of a standard approach based on a careful balancing of accuracy and applicability that can be recommended for wider application.

Evaluating advanced technology solutions

The concept of down-stream control (DSC) has been recently proposed as a technologically advanced solution to IWS (Charalambous and Shafei, 2019). The concept revolves on maintaining supply rationing at the customer end while maintaining water network pressurisation by the temporary use of automatic shut-off valves at customer connections. This allows for cost-effective network rehabilitation using mainstream leak detection and repair techniques, which leads to greater water quantities available to cover user demand. With the rapid progress in IoT technologies, this approach may allow longer and more cost-effective deployment, which translates to wider applicability at ever more challenging water scarcity situations. Other technologies may also show promise in assisting in coping with IWS, as well as facilitating sustainable transition to continuous supply.

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| 1.4 |

Membrane technology

Authors: *Xia Huang, Kuo-Lun Tung, How Yong Ng, Val S. Frenkel, Pierre Le-Clech, Emile Cornelissen, Long Duc Nghiem, Kwang-Ho Choo on behalf of the Membrane Technology Specialist Group.*

Introduction

The primary mission of the Membrane Technology Specialist Group (MTSG) is to educate professionals and the public around the globe about membrane technologies for water management, and to promote and exchange knowledge on membrane technology and membrane processes. Special attention is paid to the young professionals who will increasingly encounter membrane technologies in their professional life. The group consists of a vast spectrum of active members (scientists, researchers, engineers, membrane industry professionals and end-users) in academic, industrial, and public sectors. The group has grown to be one of the largest SGs within IWA. In recent years membrane technologies have started to play a vital role in solving water scarcity on the planet, which is in close association with global warming and climate change. The major reasons are that membranes allow not only effective separation of various contaminants from water sources to achieve the required quality but also exploration of new water resources from non-traditional sources such as wastewater for direct and indirect potable use. Beside continuous membrane operational processes, the newer concept of non-continuous or semi-batch operational processes allows further optimisation of membrane processes operation. While being invented in 1972, the forward osmosis (FO) process has finally become commercially available recently, benefitting several niche applications and industrial users particularly. Membrane technologies continue to provide benefits to mankind and improve the quality of life.

Terminology

AnMBR: Anaerobic membrane bioreactor
CAGR: Compound annual growth rate
CAS: Conventional activated sludge
CNT: Carbon nanotube
COF: Covalent–organic framework
FO: Forward osmosis
GO: Graphene oxide
HPM: High-pressure membrane
LPM: Low-pressure membrane
MBR: Membrane bioreactor
MD: Membrane distillation
MF: Microfiltration
MOF: Metal–organic framework
NF: Nanofiltration
NOM: Natural organic matter
RO: Reverse osmosis
TFC: Thin-film composite
TrOP: Trace organic pollutant
UF: Ultrafiltration
ZLD: Zero liquid discharge

Existing knowledge on SG topics

Overall membrane market

The four main membrane categories commercially available for water and wastewater treatment of water, wastewater and desalination are microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). MF and UF membranes are categorised as low-pressure membranes (LPMs), while NF and RO membranes are categorised as high-pressure membranes (HPMs).

All four membrane types are currently in high demand, with continuous increases in market shares and a high compound annual growth rate (CAGR) of 9.47% (Figure 1.7). Specifically, the ceramic membrane market shows a faster growth trend (11.7%) than the integral membrane market. Territorially, the largest market is in Asia–Pacific, which is followed by North America (Figure 1.8a). LPMs are widely utilised for water treatment, as pre-treatment to HPMs, as well as for wastewater treatment (i.e., being the “heart” of the membrane bioreactor (MBR) technology). Water and wastewater treatment constitutes more than half of the membrane market, and is followed by the food and beverage industry (Figure 1.8b). The FO market is developing rapidly, primarily with industrial applications (Arias-Paić and Korak, 2020).

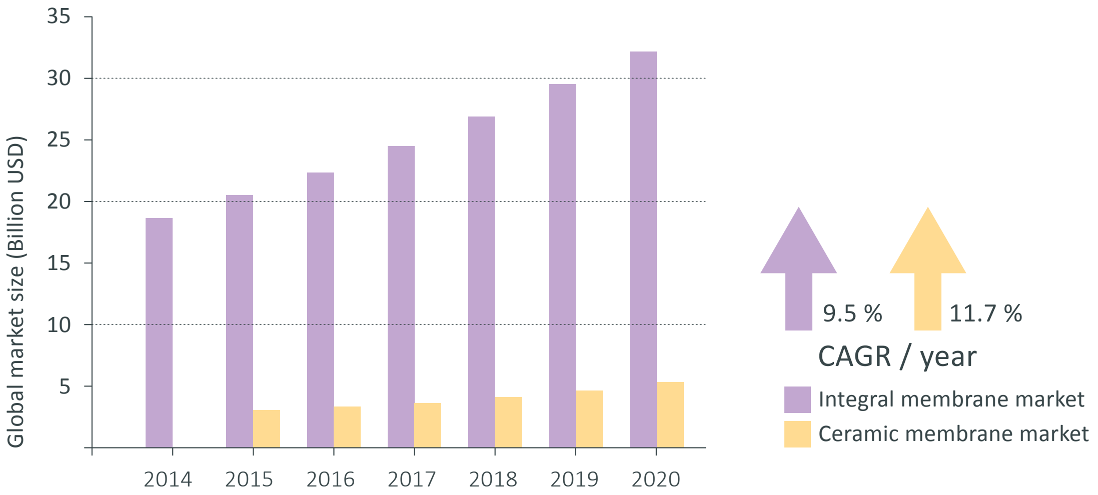
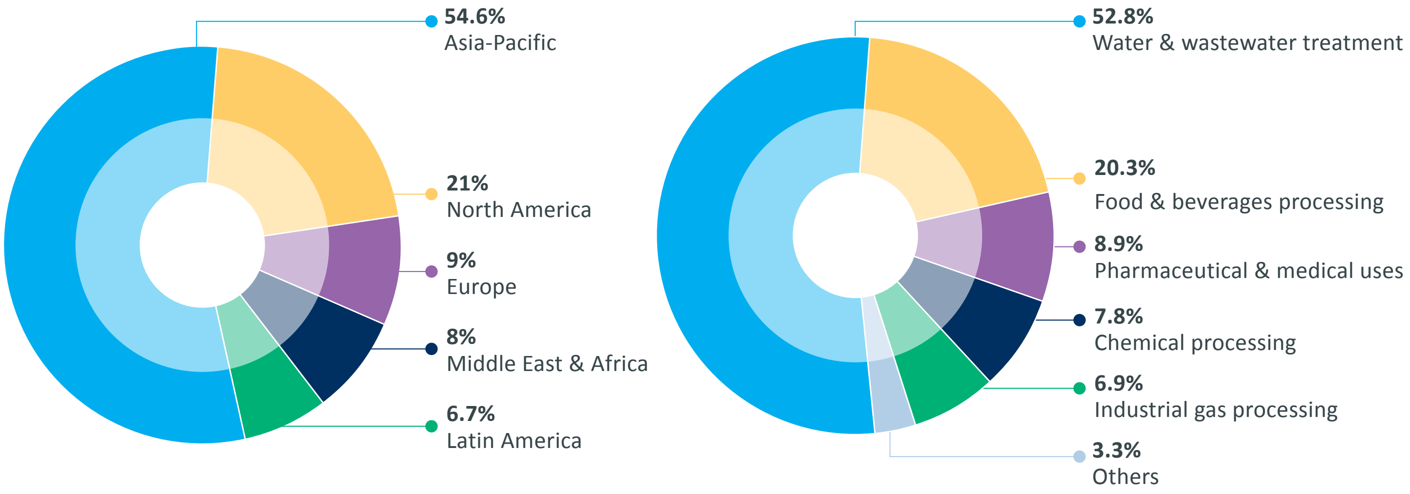


Figure 1.7 Variations of the global market size of the integral and ceramic membrane markets from 2014 to 2020 (Source: Global Water Intelligence).



(a) Market share in different regions

(b) Market share in different fields

Figure 1.8 Membrane market share in (a) different regions and (b) different application fields (Source: Global Water Intelligence).

Application in drinking water purification

MF/UF membranes are increasingly used in drinking water treatment for efficient removal of suspended particles, colloids, turbidity, algae, bacteria, parasites and viruses (only for UF) for clarification and disinfection purposes. Conventional water treatment is increasingly replaced by a combination of coagulation and MF or UF, or by powdered activated carbon treatment and MF or UF (Robinson and Bérubé, 2020). MF or UF is further used as an alternative pre-treatment to other treatment processes, such as softening, removal of micro-pollutants and nitrate removal (e.g., by using NF or RO). The quality of the MF/UF permeate is consistently better than the quality of the water from conventional treatment. Biological stability can also be enhanced when using MF/UF (Schurer et al., 2019).

NF and RO are also increasingly used in drinking water supply for disinfection, desalination, softening, and removing harmful constituents. Although only a 2.0-log reduction credit for bacterial and virus removal was assigned by World Health Organization (WHO) guidelines (2017), a much higher 7.0-log reduction virus removal was recently reported for intact RO membranes (Hornstra et al., 2019). RO membranes were furthermore reported to remove >90% nitrate, 80%–95% ammonium, >98% fluoride and >90% toxic ions (e.g., Cr(VI), As(V) and ClO_4^-). In general, the removals of pesticides, endocrine-disruptor compounds, pharmaceuticals and personal care products by RO are high but can be insufficient depending on the specific molecular properties of these micro-pollutants. Specifically, low molecular mass and hydrophilic neutral organic compounds are known to pass through the RO membranes (Albergamo et al., 2019). Although not designed to remove suspended or particulate matter from fresh water

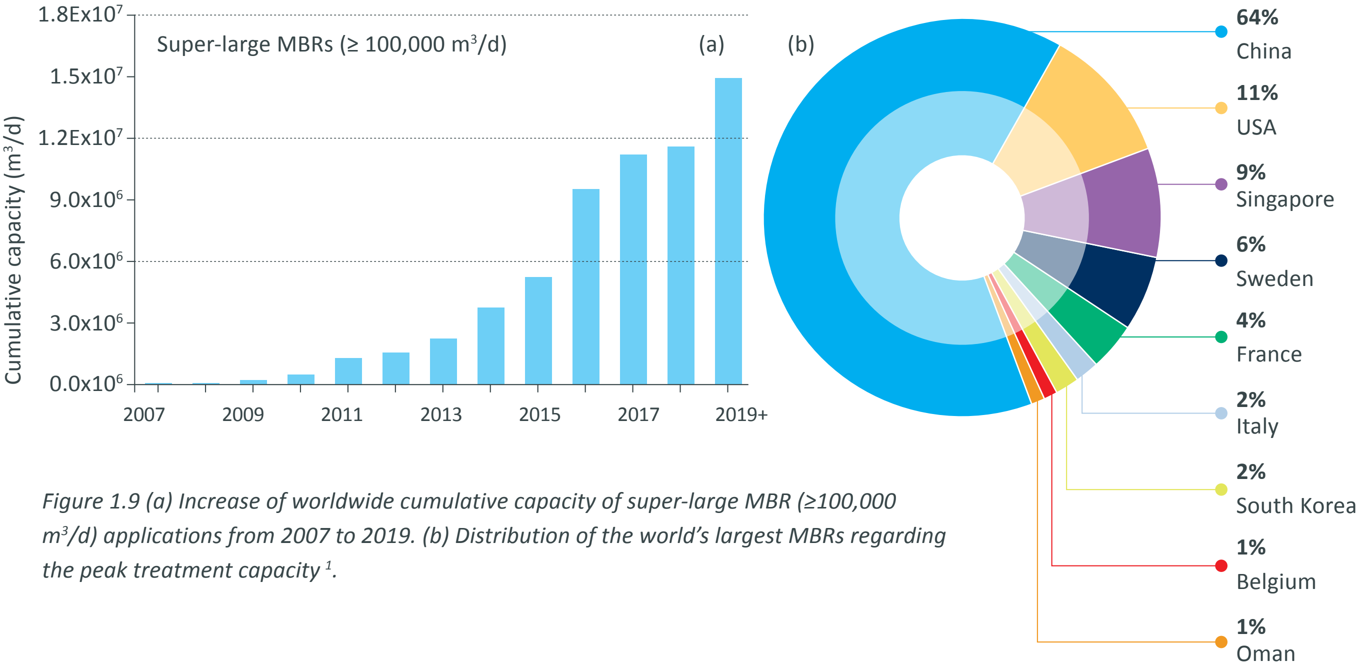


Figure 1.9 (a) Increase of worldwide cumulative capacity of super-large MBR (≥100,000 m^3/d) applications from 2007 to 2019. (b) Distribution of the world's largest MBRs regarding the peak treatment capacity [1].

sources, intact RO membranes are known to fully remove these constituents. Apart from the removal of ammonium, boron and small neutral organic micro-pollutants, all drinking water treatment goals are met using one single treatment step with the RO process.

NF has long been applied for groundwater softening and natural organic matter (NOM) removal with partial desalination. Most NF membranes have a NOM rejection of >90%. The United States Environmental Protection Agency lists NF as one best available technology (BAT) for NOM removal. Recently, NF is increasingly applied for the removal of organic micro-pollutants. Rejection of micro-pollutants by NF is usually somewhat lower than that by RO, and it varies substantially depending strongly on the type of NF membranes and type of micro-pollutants (Zhao et al., 2017). It is more preferable to employ NF when the target micro-pollutants have relatively large molecular masses and when other water quality issues (e.g., NOM) also need to be resolved.

Application in municipal wastewater treatment and reclamation

MF and UF are the most widely used membrane technologies in the field of municipal wastewater treatment and reclamation. The most typical application is MBR, which has achieved rapid growth with ever larger installations worldwide. By 2019, there are over 60 super-large (≥100,000 m^3/d) MBR-based plants installed worldwide. The global cumulative capacity of MBRs had probably reached somewhere over 20 million m^3/d (Figure 1.9a shows the cumulative capacity of super-large MBRs over the years, most of which are for municipal treatment), roughly accounting for ~5% of the world's wastewater treatment capacity [2]. A large proportion (~64%) of the applications occur in China (Figure 1.9b).

Owing to the advantages of membrane separation, most full-scale MBR-based plants ensure high effluent quality and stable treatment performance. An extensive review of the removal rates of key water quality indicators in full-scale MBRs revealed COD and NH_4^+-N removal efficiencies to be above 95%, while TN and TP removal efficiencies are above 80% and 90%, respectively. MBRs can effectively remove most of the pathogenic bacteria and a certain portion of pathogenic viruses (Harb and Hong, 2017), and have achieved ~1.1–7.3 log removal of typical antibiotic resistance genes, which is 1 to 3 orders higher than the ~0.4–4.2 log removal of the conventional activated sludge (CAS) process (Li et al., 2019). MBR also possesses a certain removing capability for trace organic pollutants (TrOPs). A review of published data indicated that a high TrOP removal of >95% was achieved for 34 out of 79 typical TrOPs in full-scale MBRs. As compared with the CAS process without tertiary treatment, MBR performs better in removing some types of TrOPs (especially for refractory TrOPs) due to complete retention of suspended solids and higher biomass concentration at a longer solids retention time (Siegrist and Joss, 2012). MBR also has advantages in removing microplastics, where conventional secondary sedimentation has been widely reported to be insufficient in removing microplastics. Recent research (Lares et al., 2018) reported that MBR can achieve up to 99.9% removal of microplastics, owing to the superior retention ability of the membrane and suggesting a promising solution to the microplastic contamination issues.

In general, treatment cost in terms of either capital or operating cost of the MBR has become comparable to that of the CAS processes with tertiary treatment included, which is required to achieve a comparable water quality to that attained by an MBR (Iglesias et al., 2017). Although still relatively high, the cost of the MBR has decreased over the

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[1] *http://www.thembrsite.com/, accessed in January 2020*
[2] *http://www.thembrsite.com/, accessed in January 2020*

years and is approaching that of the CAS. MBR also offers a markedly smaller footprint than CAS (Xiao et al., 2019). Further wide-scale application of MBR is still challenging due to the energy consumption issue (largely owing to membrane fouling).

Application in industrial wastewater treatment and zero liquid discharge (ZLD)

Wastewater discharge regulations are becoming more stringent in developed countries and developing countries because of source water contamination and *de facto* water reuse causing serious public health concerns. Spending on LPMs and HPMs by the industrial sector (i.e., water and wastewater treatment) in 2020 is estimated to be approximately 267 and 740 million USD, respectively (GWI, 2017). The East Asia and Pacific region has the largest market, owing to industrial activities related to electronics, coal, chemicals, and power. MBRs applied for industrial effluent treatment are operated at relatively low membrane fluxes compared with municipal applications, with the lowest membrane flux level for landfill leachate treatment (Judd, 2016). Anaerobic MBR (AnMBR) has become attractive for industrial wastewater treatment such as pharmaceutical (Svojitka et al., 2017), food industry wastewater (Jeong et al., 2017) and landfill leachate (Trzcinski and Stuckey, 2016) because of reduced energy consumption and biogas recovery. RO process is most popular for industrial wastewater reclamation and reuse in combination with MF/UF or MBR treatment (Davenport et al., 2018; Gündoğdu et al., 2019). However, the treatment of RO concentrate is still challenging due to high salinity and membrane fouling. Membrane distillation (MD) could be an attractive option for ZLD while recovering valuable material from the concentrate through crystallisation (Quist-Jensen et al., 2017). MD is more cost-effective than conventional thermal evaporation and mechanical vapor compression in ZLD application (Schwantes et al., 2018; Tong & Elimelech, 2016). MD has several merits over other ZLD processes such as high salinity feed supply, low pressure operation and low fouling propensity. However, further studies on prevention of membrane wetting and scale-up of MD processes are needed.

Application in seawater desalination

Seawater desalination provides a reliable supply of drinking water, independent of the weather condition. Of the current 16,000 desalination plants that produce 95 million m3/day of drinking water globally, RO accounts for 84% of the total number of plants and 69% of the total desalination capacity [3].

Considerable growth of the desalination market is expected over the next decade. The CAGR of the global desalination market is estimated at 7.8%–10%. While the Middle East will continue to dominate the global desalination market, South and East Asia will also see the strongest market performance due to population growth and conomic development in the region. Successful transition toward wind and solar as a major energy source has also resulted in considerable energy cost reduction, and hence, the cost of water production by RO (Kettani and Bandelier, 2020). Recent project tenders in Abu Dhabi and Saudi Arabia have seen desalinated water at below 0.50 USD/m^3 for the first time.

New research trends in seawater desalination have also emerged in recent years (Jones et al., 2019; Biesheuvel et al., 2022). After decades of fruitful research to develop high rejection and high permeability membrane materials (Biesheuvel et al., 2022), the focus has shifted toward the environmental impact of seawater desalination, especially in decarbonisation and sustainable brine management. The grand challenge to decarbonise seawater desalination has been specifically highlighted by a seminal discussion by Emeritus Professor Tony Fane. Improvements in pretreatment, fouling prevention, module and spacer development, membrane integration, and brine management have the potential to more than halve the net energy of RO desalination (Fane, 2018). New research to develop low pressure NF membranes as pre-treatment to RO has also shown promising results in terms of fouling and energy reduction as well as scalability (Labban et al., 2018). Last but not least, given recent progress in molecular biology and new quorum sensing insights into the way biofilms form and disperse, a major breakthrough in biofouling prevention is expected possibly within this decade (Oh et al., 2017; Rehman et al., 2019).

General trends and challenges

Enhancing membrane performance with new materials and fabrication processes

Next-generation membranes for water treatment are mainly being developed by incorporating nanomaterials such as particles (three dimensional, 3D), sheets (two dimensional, 2D), or fibres (one-dimensional, 1D) to improve membrane properties, performance, and anti-fouling capability (Nunes et al., 2020). The 3D materials include metallic oxide nanoparticles, silver nanoparticles (nAg), mesoporous metal–organic framework (MOF) nanoparticles, covalent–organic framework (COF) nanoparticles, quorum quenching nanoparticles and so forth. The 2D materials include graphene oxide (GO), MXene, MoS2, and nano-porous COF, as well as MOF nanosheets. The 1D materials include carbon nanotubes (CNTs), metal hydroxide nano-strands, cellulose nanofibres and so forth. These membranes generally possess high permeability, much greater resistance to breakage and/or enhanced anti-biofouling capability. According to membrane structures and nanomaterial locations, five types of nanocomposite membrane can be fabricated including (a) conventional mix-matrix membranes (MMM), (b) surface-coated membranes, (c) thin-film composite (TFC) membranes

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[3] *www.desaldata.com*

with nanocomposite substrate, (d) thin-film nanocomposite (TFN) membranes and (e) surface located TFN membranes with engineered nanoparticles (ENP) (Wen et al., 2019; Yang et al., 2019). Membrane processes based on even more advanced nanoscale control of membrane architecture may ultimately allow for multi-functional membranes that not only separate water from contaminants but also actively clean themselves, check for damage, detect contaminants or combine detection, reaction and separation functions.

Almost all membrane materials require an intrinsic hydrophilic characteristic to prevent fouling. The MD process uses hydrophobic porous membranes as an intermediate liquid/vapor interface where vapour transports through the membrane pores by diffusion. There are three major challenges for traditional MD processes and materials (Elimelech and Phillip, 2011; Dongare et al., 2017) including temperature polarisation, low energy efficiency and low resistance to pore wetting. Preventing the through wetting of membranes by low-surface-tension liquid attracts much attention. Anti-wetting (Alkhudhiri et al., 2012), omniphobic (Chen et al., 2018) and Janus (Yang et al., 2017; Zou et al., 2020) membranes have been developed to enhance wetting resistance. The group led by Q.L. Li et al. (Dongare et al., 2017; Wu et al., 2017) developed a novel direct solar MD process that utilises a photothermal nanoparticle coating to capture sunlight and converts it to heat at the membrane surface, providing the thermal driving force for the MD process. This approach overcomes the major limitation of temperature polarisation encountered in conventional MD processes and significantly increases the energy efficiency of MD.

Membranes are categorised into two main segments: inorganic and organic. Organic membranes are primarily polymeric membranes that presently dominate the membrane market. Inorganic membranes can be further classified into ceramic and metallic membranes. Materials of the inorganic membranes include oxide mixtures and sintered metals. Inorganic membranes have received considerable attentions due to their superior chemical, thermal and mechanical stability. They are therefore ideal candidates for harsh water purification processes, such as industrial wastewater treatment and oil/water separations (Chen et al., 2017). Common fabrication methods for inorganic membranes include slip casting, tape casting, pressing, extrusion, dip coating, sol–gel process and atomic layer deposition. Recently developed methods include thermal spray coating (Lin et al., 2012) and 3D printing (Low et al., 2017).

Membrane-based processes for energy and resource recovery from wastewater

AnMBR technology has gained attention lately because of its potential for energy and resource recovery. Following successful demonstrations of the aerobic MBRs, both cross-flow and submerged AnMBRs have been commercially applied for treating industrial wastewaters (Lin et al., 2013). Nevertheless, although AnMBR has shown to be a promising technology for treating municipal wastewater in the literature with lab-scale systems, full-scale applications have yet to be realised because of low sustainable membrane flux and membrane fouling (Lei et al., 2018). As such, the performance of the AnMBRs needs to be further improved to gain greater acceptance. One of the keys is to control membrane fouling. The common fouling mitigation measures can be classified into three categories: physical, chemical and biological, with many belonging to overlapping categories. For example, the addition of chemical additives such as powdered activated carbon or ferric chloride (Dong et al., 2015) changed both the chemical and physical properties of the anaerobic mixed liquor. Recirculation biogas sparging and adding carriers are other popularly applied fouling control strategies. Regardless, these mitigation measures must be applied in combination and in tandem with optimised operational conditions and regular membrane cleaning. Other recent developments include rotating/vibrating membranes (Lei et al., 2018, Wang et al., 2021) and quorum quenching (Liu et al., 2019, Aslam et al., 2018).

Resource recovery by the AnMBRs is a significant draw for their practical applications in real world industries since the membrane fouling issue has brought about high operational costs. While biomethane has been generally viewed as the main resource recoverable from the AnMBRs, other products such as biohydrogen and volatile fatty acids may also be recovered, albeit at the expense of biomethane production. The best overall value of each resource should be determined through detailed economic and environmental assessments (Khan et al., 2016) and further improvements in technology including recovery of dissolved methane.

Integrated membrane processes for advanced water and wastewater treatment

Despite the wide range of applications, further development of membrane technology is still hindered by drawbacks and limitations. For example, all types of membrane technology suffer from membrane fouling; and the LPMs can hardly remove low molecular mass dissolved contaminants. Combining membrane process with some chemical processes could bring about synergistic effects such as improved separation performance and alleviated membrane fouling, resulting in a wealth of novel integrated membrane processes. A large part of the advances were accompanied by the development of functional membranes (e.g., electro-, photo- or chemo-catalytic membranes), which allow both physical filtration and chemical reactions. For example, electro-catalytic membrane reactors contain conductive membranes which directly oxidise (or reduce) pollutants or generate reactive species (e.g., xOH, H_2O_2, et al.) at the cathodes or the anodes, thus achieving pollutant degradation during the filtration (Zhu and Jassby, 2019) and even leading to mutual enhancement. On one hand, the filtration process enhances the mass transfer of pollutants to the membrane surface and simultaneously increases reaction area, thus improving degradation efficiency (Fu and Zhang, 2018). On the other hand, the electro-catalytic process reduces the accumulation of pollutants on membrane surfaces, thereby alleviating membrane fouling. Such integrated processes also make up for the deficiency of conventional LPMs, which hardly remove small-molecule contaminants (Gayen et al., 2018). Photo-catalytic membranes can be prepared from photo-catalysts such as TiO_2 (Fischer et al., 2014). With light irradiation, electron-hole pairs are generated adjacent to the photo-catalytic membrane surface, whereby giving rise to reactive oxygen species which degrade organic pollutants in water (Leong et al., 2014). The photo-catalytic reaction during filtration can remove organic substances under mild conditions and reduce membrane fouling (Sun et al., 2020).

Further development of catalytic membrane processes may include enhancement of the catalytic effect and increase the contact time between the powerful oxidants and the contaminants by further developing functional membranes and optimising membrane module design and operation of the processes.

Robust and cost-effective fouling control for engineering applications

Membrane fouling is still a bottleneck challenge for extended applications of membrane technology. Although membrane fouling has been extensively studied for decades in the academic field, there is a great need to bridge the gap between lab-/pilot-scale knowledge and full-scale applications. Feed composition, flow dynamics and foulant layer evolution in full-scale applications are normally much more complicated and heterogeneous than those in lab-/pilot-scale studies. From the perspective of practical engineering applications, the strategies for membrane fouling control need to be developed in the following aspects:

(a) Membrane materials and devices: Systematic assessment selection and practicable treatment of membrane materials to resist attachment of organic/inorganic/biological foulants and be more tolerant to chemical cleaning (Meng et al., 2017), and improved design of the membrane module/cassette/tank to optimise the hydrodynamic conditions (Wu et al., 2018);

(b) Operating conditions: Refined conditioning of the feed suspension/solution for more targeted control of the foulant concentrations or physicochemical properties (She et al., 2016), and optimisation of operation conditions such as membrane flux, cross-flow rate, running cycle, relaxation interval and scouring conditions (Judd, 2016);

(c) Membrane cleaning: Development of more efficient agents and cleaning modes in full accordance with the complexity of membrane fouling, with attention placed on the long-term evolution of latently stubborn biofouling (Wang et al., 2014);

(d) Process management: More precise full-process management of the fouling potential (from the pretreatment unit to the membrane unit) with careful consideration given to the spatial heterogeneity (e.g., inter-stage and intra-stage differences in fouling in NF and RO processes) (Li et al., 2020), and incorporation of intelligent technologies such as remote monitoring, automatic feedback control and big data analysis to detect, diagnose and control fouling more smartly (e.g., early warning of fouling potential, real-time monitoring of foulant properties and timely control of seasonal and temporal fluctuation in fouling).

The cost-effectiveness of fouling control strategies needs to be balanced for practical engineering applications. Constant efforts are required to reduce the operating cost in terms of energy consumption, chemical agent consumption and so on (Park et al., 2020). Taking membrane scouring (or cross-flow) as an example, more energy-efficient aeration or water flow modes (such as variable-frequency aeration, intermittent aeration, pulsed modes and feedback control with automatic functions) can be developed for full-scale applications (Meng et al., 2017; Sun et al., 2016).

Management of ageing membrane

RO membranes used in desalination usually need to be replaced every 5–8 years (several times in a plant's lifetime), with typical replacements being in the order of one thousand elements for each 10,000 m^3/d of installed product water capacity. This will undoubtedly lead to a significant increase in the number of spent modules. At present, no option, other than landfill discharge, is proposed to membrane users. Additionally, there is an environmental impact associated with discarding the potentially valuable manufactured devices. While this trend is clear for RO in desalination, a similar observation can obviously be made for most of the common membrane applications in the water and wastewater industry.

It is critical to minimise these environmental impacts by increasing the lifecycle of the membrane elements via a secondary use or material reuse and, thereby, lower the carbon footprint and improve sustainability of the technology. Secondary benefits are to the water and wastewater stakeholders looking for lower-cost membrane systems from reclaimed seawater desalination modules which would be verified for effective performance at lower specifications. Recent research activities, mostly in Australia and Spain, have been able to further quantify those benefits and to propose new considerations for the reuse, recycling and alternative disposal of end-of-life modules. Many challenges are faced by the concept of membrane recycling, including their appropriateness for reuse in humanitarian environments (Lawler et al., 2012; Garcia-Pacheco et al., 2018). Some companies, like Water Surplus in the USA and Aquatip in Australia, have also been developing business models around management of second-hand membranes.

Future opportunities lie ahead for various academic and industry stakeholders, including the supply of inexpensive, second-hand but reliable, resilient and safe membranes that could potentially be used (e.g., for RO pretreatment). The use of converted membranes to produce safer water to remote communities is another option requiring further study and assessment. Studying second-hand membranes can also help to develop knowledge on the current membrane markets, along with environmental impacts associated with production and disposal of membranes. Finally, a better understanding of the mechanisms occurring on membranes during cleaning and/or chemical attack, often resulting in integrity failure, is also necessary. This will benefit the research community for future studies based on the development of more chemically resistant membrane materials.

Conclusions

The vigorous development of membrane technology in water and wastewater treatment will continue with a larger market share in the future. The application potential of membrane technology is expected to be further enhanced in the next 5–10 years, based on further progress in multiple fields including advanced membrane materials with desired characteristics (e.g., higher flux, higher selectivity, anti-fouling, extra-functions, etc.), more effective integrated processes for advanced treatment, novel extensions for resource and energy recovery and more reliable fouling control strategies for stable operation. In addition, the prolongation of membrane service life and implementation of lifecycle analysis will make a great contribution to the improvement of the sustainability of membrane technology.

Considering the inherent advantages and predictable future development, membrane technology will provide more convenient and efficient solutions for water and wastewater treatment, thus further approaching the goal of sustainable development.

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Modelling and integrated assessment

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Introduction

The objective of the MIA Specialist Group (SG) is to address and promote all aspects of modelling, simulation, and formal methods of applying systems analysis to manage and improve the quality of the aquatic environment. This includes the development and application of mathematical models and modelling tools, such as optimisation algorithms, time-series analysis and forecasting, computational procedures for decision analysis and support, uncertainty analysis, experimental design, meta-modelling, etc. In the current climate, characterised by more stringent water quality demands and simultaneous digitalisation of the water sector, development of "fit for purpose" computational decision-making tools is crucial. Finding optimal solutions to address more and more complex challenges requires a balanced and integrated approach, combining existing physical and expert knowledge with information from data sources that are becoming more and more abundant and diverse. The SG stimulates knowledge transfer between academia and industry and between different areas and disciplines within the water cycle. The SG maintains a forum for discussing inter-disciplinary issues within IWA in order to augment the different elements of problem-solving with those having engineering, economic, social, institutional (legal, governance) and cultural dimensions. In this way, the SG promotes development and use of systematic procedures for addressing complex challenges in a multidisciplinary fashion, more generally known as integrated assessment. The content of this contribution is based on a survey among the members of the MIA SG, carried out October–November 2019 and still valid, where different topics where selected and prioritised. The selected top five "hot topics", (i) Life Cycle Assessment, (ii) Climate-Water-Energy-Food Nexus Modelling, (iii) Modelling Integrated Urban Water Systems, (iv) Trends and Challenges in Computational Fluid Dynamics applied to WRRFs and Drinking Water Treatment, and (v) Uncertainty and Risk Modelling, are discussed in this publication. The SG also has two conference series under its wings, i.e. Watermatex (every 4 years) and WRRmod (every 2 years).

Existing knowledge

The MIA SG is strongly committed to the organisation of several Task Groups (TGs) and Working Groups (WGs). As a result, considerable SG knowledge has been summarised and compiled in Scientific and Technical Reports (STRs), which are typically the end-product of a TG. Previous STRs are currently available on topics such as Respirometry (Copp et al., 2002), River Water Quality Model No. 1 (Reichert et al., 2001), Guidelines for Activated Sludge Modelling (Rieger et al., 2012), Benchmarking of Control Strategies (Gernaey et al., 2014), Uncertainty in Wastewater Treatment Design and Operation (Belia et al, 2021), Minimising Wastewater Utility Greenhouse Gas Footprints (Ye et al., 2022), Computational Fluid Dynamics Modelling (Laurent et al., 2022) and Physicochemical Modelling (Batstone et al., 2022).

General trends and challenges

The water industry is being transformed, and digitalisation is a key focus in this transition. However, "digitalisation" and its derivatives, such as "digital twins" and "machine-learning", seem to be buzzwords that are used without sufficient consensus and in-depth understanding of the challenges and development needs ahead.

An important challenge relates to efficient model-development for real-time decision making in integrated water systems. Optimal interaction is needed between models and the continuously increasing abundance of data. This will require consensus and guidelines on the state-of-the-art and integration between models based on first principles and data-driven tools. At the Watermatex 2019 conference, Professor P. Vanrolleghem delivered a keynote address on the topic of Digitalisation of Water (Vanrolleghem, 2019), its history and potential consequences for the water sector. Two workshops at the WRRmod2021 were also focussing on this. One, on the transition from traditional models to digital twins, was aiming at reaching a consensus within the modelling community on the definition of digital twins. Outcomes of this discussion was a position paper submitted to *Water Science and Technology*. The second workshop focused on hybrid modelling as a tool for the future.

A second important challenge presented to the MIA community is the shift of focus in the wastewater industry from the conventional paradigm of treatment to a new and wider vision for extraction of resources from wastewater in Water Resource Recovery Facilities (WRRFs). During the closing session of WRRmod2018, a constructive debate on future challenges and opportunities for water and resource recovery modelling was organised and some consensus on future challenges for the modelling community was reached. A comprehensive summary of key thoughts and opinions that were expressed at that time was prepared by Regmi et al. (2018). Many of these outlooks can be applied in the broader context of integrated water systems modelling. Another workshop at WRRmod2021 further explored this topic.

Both challenges have some common demands:

- **Need for multidisciplinary collaboration**
  The wider vision for WRRFs shifts the focus from water quality to a vision that targets combined social, economic, and environmental goals. Conventional process models must be extended with new approaches, such as physicochemical models (Batstone et al., 2012; Batstone, 2022), effective cost and price models for economic assessment of the water value chain (Rahman et al., 2016), and greenhouse gas (GHG) models (Mannina et al., 2016). Furthermore, extended models need to be integrated within broader frameworks (e.g., Life Cycle Assessment to comprehensively account for environmental aspects such as resilience assessment, and broader environmental impact studies) at various scales (e.g., sewershed, watershed), thereby allowing decision-makers to make environmentally sound choices on the most cost-effective process design and best process operation. Similarly, to successfully implement digital solutions in the water sector, stronger interaction will be needed between developers of instrumentation, modellers, and the different stakeholders in the water cycle.

- **The impact of data abundance and digitalisation**
  Increased data availability, in combination with improved computational capacity, will shape the structure of future modelling frameworks. Users and developers of models will have more opportunity to make use of much more (online) data and data of various types (e.g., images from cameras, operational log books, spectra from analysers, outputs from acoustic sensors, energy pricing, etc.) which will bring about the development of hybrid or grey-box models. Combinations of Machine Learning and Artificial Intelligence techniques with physical process knowledge and existing modelling frameworks based on first principles (e.g., Lee et al., 2005) will emerge as dominant, powerful modelling frameworks that can be applied to solve real-time problems.

- **The impact of data quality**
  Within this shift to new modelling paradigms, the impact of data quality on model development will be crucial. At the same time, the impact of models on data quality will also be of great consequence. Data will feed models, and models will feed data, as part of automated methodologies identify, correct and replace poor or missing data (e.g., De Mulder et al., 2018; Le et al., 2018). Such systems are likely to include automated mass balance calculations and soft-sensor-based diagnostic checks for outliers and other unusual conditions.

- **Accessibility of available information sources**
  As a final important development need, the development of tools to help to visualise, interpret and interact with calculated model results and available data sources should be stressed, so that information becomes valuable for a more diverse audience or stakeholders, including water customers

Life cycle assessment

Life cycle assessment (LCA) has been widely used to quantify environmental impacts associated with urban water infrastructure, including water resource recovery facilities (WRRFs). Within the current paradigm shifts, in which the focus of WRRFs has changed from pollutant removal to resource recovery and there has been a shift from centralised to decentralised treatment, LCA can play an important role by evaluating new technologies and processes in terms of overall environmental sustainability and capturing trade-offs from one area of environmental concern to another. As a quantitative environmental assessment method, LCA serves as a useful decision-support tool for examining alternative future operational scenarios during strategic planning within the water sector. To date, however, there is no single body of work that provides systematic guidance to researchers and practitioners on how to conduct LCA studies for WRRFs during all stages of their life cycle.

The MIA Working Group for LCA of water and wastewater treatment (LCA-Water WG) has been working in recent years to develop a series of recommendations for conducting LCA studies in the wastewater treatment sector, supported by state-of-the art research outcomes. The LCA-Water WG provides (1) examples of questions that can be addressed (and cannot be addressed) by LCA; (2) background information on the selection of the methodological approach (e.g., attributional versus consequential, process-based versus input-output); (3) guidance on the selection of the functional unit and on the definition of system boundaries; (4) recommendations on how to conduct an inventory; (5) guidance on the selection of indicators and impact assessment methodologies; and (6) recommendations for the interpretation of results to facilitate decision-making. These recommendations are now ready, after reaching consensus among members of the LCA-Water WG.

The recommendations were presented and discussed in a workshop organised at Watermatex 2019 in Copenhagen, Denmark. The outcome was positive, and the audience showed a high level of trust in the recommendations. We believe that these recommendations will guide future LCA studies in our field. With these guidelines, the LCA-Water WG has completed its mission and will end a journey that has taken nine years (Corominas et al., 2020). Nevertheless, LCA methodologies are continuously being updated and the wastewater treatment sector is sure to continue this journey.

Climate-water-energy-food nexus modelling

Climate change influences water in the hydrological system, energy and food production, and, as global population increases (and also urbanisation), major impact on the future of humanity is inevitable. Water is the primary indicator of this development, and climatic extremes are already more common causing dry regions to become drier and wet regions to become wetter. The consequences for water supply and water quality are becoming increasingly erratic.

The climate–water–energy–food nexus is real, and we need to address the challenges caused by these close couplings (Figure 1.10). A strategically developed scientific framework is needed to model the interlinkage of these systems. Modelling the nexus of climate, water, energy and food advances our course towards achieving the United Nations' Sustainable Development Goals (SDGs), including concerns about food security and sustainable agriculture (SDG 2), universal access to water and sanitation (SDG 6), universal access to affordable, sustainable, and modern energy (SDG 7), and combating climate change impacts (SDG 13) in an interlinked conceptual approach. Much effort has already been invested through other initiatives, such as the EU COST Action "Circular Cities".

Modelling is an essential tool for early warning and control actions. Some apparent needs for models that will provide a basis for prediction and warning are as follows:

- The combination of measurements and models to predict flooding events;
- Prediction of high flow rates to WRRFs;
- Water resource utilisation and pollution risks;
- Energy use and GHG emissions;
- Effectiveness of complementing existing practices with novel nature-based solutions; and
- Environmental impacts of agricultural activities.

The goal is to make both urban settings and WRRFs more resilient, and to attain the concept of integrated management of our natural resources, which will ultimately result in increased resource utilisation efficiency and minimal environmental impacts.

Agriculture requires about 70% of all water withdrawals globally. With increasing population and urbanisation, water demand for industrial and domestic use will increase, putting a high stress on more efficient irrigation. Modelling the relationships between soil moisture content and irrigation demands is one important area of research to make agriculture more water efficient. Models that can use weather data to predict the amount of rain that will fall on land will also be needed. This will help farmers to manage fertilisers and chemicals to protect both the soil and water resources. Such a task would, of course, require competence outside IWA and collaboration with other organisations.

Groundwater constitutes the largest reservoir of freshwater in the hydrological system, accounting for over 97% of all freshwaters on earth, and is an important resource for industry and agriculture. Planned and coordinated management of water resources for long-term sustainability requires an integrated modelling approach.

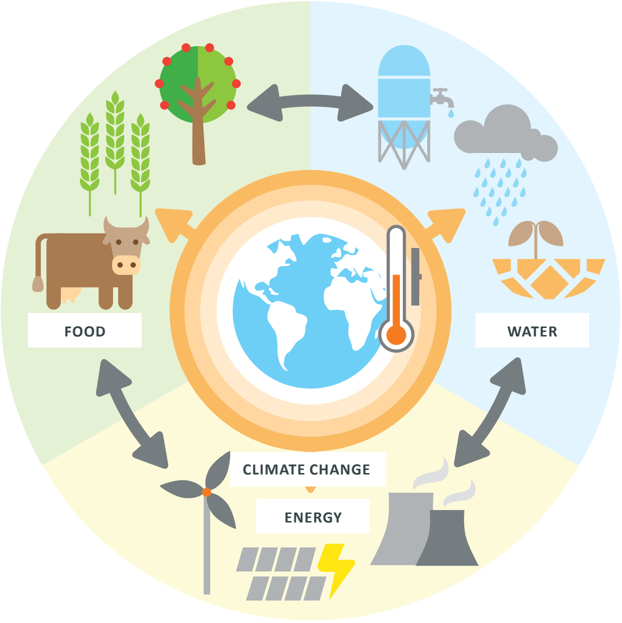

Figure 1.10 Climate–water–energy–food nexus

Urban water cycle operation must be more integrated, requiring both water quantity and quality models. Energy balances are needed for the urban water cycle, including water abstraction and distribution, consumer use, sewer thermal and organic energy content, as well as in treatment plants. Each urban water system is different in terms of configuration, elevations, demands, water source types, etc. The ability to collect information from remote devices and correlate that information across diverse systems will help us achieve near-real-time models for prediction and warning. Increasing digitalisation relying on massive instrumentation and IoT will provide a huge potential for more accurate models (Olsson, 2015; Olsson, 2019).

Models are needed to describe sources of GHG and their influence. Nevertheless, condition-based instead of time-based maintenance, can be significantly aided by models for leakage detection, and for energy consumption in the water cycle. For the urban water planner, it will be important to know the required energy and the amount of GHG inherent in the production of every cubic metre of water. The ultimate requirement is to minimise the footprint of water operations.

The use of nexus theory in various constellations has become an acceptable approach to integrated resource management (Olsson, 2015). Climate–water–energy–food nexus modelling is a useful tool to support the sustainability and inclusive socio-economic development in water scarce regions of the world, from which coherent policies could be derived.

Modelling integrated urban water systems

Integrated urban water systems modelling has aligned itself with several key research trends in the past few years. A few dominant trends include (1) expansion of model scope, new types of models and new ways of integrating models; (2) new paradigms in data gathering and monitoring; and (3) an evolving mindset and increasing engagement of stakeholders. Much of the existing integrated modelling philosophy remains unchanged. However, greater involvement of stakeholders in the modelling process has encouraged more exploratory approaches and scenario analysis, which in turn have driven the need for faster and simpler models.

At the forefront of integrated model development is the challenge of building fit-for-purpose, parsimonious models that reliably address modelling aims. Establishing the link between conceptual models and detailed hydraulic models remains a challenge (Kroll et al., 2017), but has progressed in recent years, particularly in the context of urban flood modelling (Jamali et al., 2020; Löwe et al., 2017) and compartmental reactor models designed using CFD. Integrating urban flood modelling with other aspects of the urban water infrastructure has been of key interest. With increasing availability of new forms and formats of data (Eggimann et al., 2017), some have explored more data-driven and highly conceptualised approaches to building faster models (Kroll et al., 2017) by either linking sub-systems that have been underexplored (e.g., flooding), enabling these models to be used in long-term simulations (Jamali et al., 2020) or by exploring uncertainties in larger integrated models through systems analysis (Tscheikner-Gratl et al., 2019). Machine learning techniques are also increasingly used as surrogates for intensive hydrodynamic simulations (e.g., Berkhahn et al., 2019; Leitao et al., 2018) but are not yet practically applicable.

Nature-based solutions (NBS), also known as Low Impact Development (LID), Water Sensitive Urban Design (WSUD) and Sponge Cities (Fletcher et al., 2015), are increasingly being considered in policy and, in turn, in integrated urban drainage models. The capability of NBS in providing ecosystem services and multiple benefits to our cities (e.g., Kuller et al., 2017) has legitimised their investment and uptake in policy (European Commission, 2020). However, no suitable models currently exist that can provide a comprehensive and integrated evaluation. Furthermore, a large proportion of urban water infrastructure is nearing the end of its functional lifespan in many cities. Researchers are tackling the centralisation versus decentralisation debate by looking towards integrated modelling of either the disconnection of existing infrastructure (Baron et al., 2016) or implementation of NBS (Deletic et al., 2018). EPA SWMM (Rossman, 2010) remains the model of choice for simulating NBS performance, and little effort has been made to improve its current capabilities. The focus has been on simulating broader multiple-benefits and multi-faceted aspects including, for example, agent-based models that mimic stakeholder decision-making (Castonguay et al., 2018) or simplified models that model the impact on urban microclimate (Broadbent et al., 2019).

Similar trends are also seen in the simulation of “traditional grey infrastructure”, where conceptual representations of sewer systems, for example, are being explored to enable scenario analysis and exploratory modelling of possible future transitions (Duque et al., 2020; Bakhshipour et al., 2019; Eggimann et al., 2015). Aside from these developments, integrated models have expanded their focus beyond the urban water system to incorporate knowledge from other disciplines. Notable examples in recent literature include the link with GHG emissions modelling (Mannina et al., 2018), urban development and future cities planning (Hargreaves et al., 2019; Löwe et al., 2017) and urban climatology, in particular, the Urban Heat Island effect which is prevalent in many cities (Meili et al., 2019). Attempts to link urban drainage with water supply modelling remain limited (e.g., Sitzenfrei et al., 2017) but should be encouraged since water reuse has become topical with the increasing number of water-stressed cities and the viability of rainwater and greywater reuse.

Two pathways are observed for the collection of data for integrated models. On the one hand, cheaper and low-power sensor technology has enabled the setup of large-scale monitoring campaigns that can instrument and collect data at high spatial and temporal resolutions (e.g., Blumensaat et al., 2017). This is in line with new emerging paradigms, such as the “digital twin” or the “Internet of Things” (IoT). New forms of data are increasingly emerging (Eggimann et al., 2017), and there also appears to be broader acceptance and use of open data standards globally, both of which drive the application and integration of machine learning techniques. With greater acceptance by stakeholders and cost-effectiveness of the monitoring equipment, large-scale monitoring and modelling systems for water bodies, public health, flood risk and coastal systems have been established in several cities (e.g., Badevandsudsigten in Denmark, the early flood warning system in the United Kingdom and the Port Phillip Bay public health risk monitoring program by the Victorian Environment Protection Authority in Melbourne, Australia).

Finally, at the practical level, integrated urban water systems modelling has seen increasing acceptance and uptake in the industry. Stakeholder involvement has enabled modellers to better understand the interactions and conflicts between multiple objectives in the planning and modelling process (e.g., Skrydstrup et al., 2019). Notably, serious gaming has evolved into a potential platform for better engagement and communication between different stakeholders involved in managing urban water systems (e.g., The Academy by DHI, 2020; Savic et al., 2016). This has been applied at different stages of the urban wastewater system management life cycle, i.e. planning, stakeholder engagement, design and operation. Undoubtedly, this greater involvement of practitioners will benefit integrated model development through refinement of modelling aims, development of key quantifiable objectives spanning sectors and disciplines and the creation of faster, more efficient, exploratory and fit-for-purpose models for integrated assessment.

Trends and challenges in computational fluid dynamics applied to WRRFs and drinking water treatment

Computational fluid dynamics (CFD) has become an increasingly used tool in the field of both wastewater and drinking water treatment (Samstag et al., 2016; Laurent et al., 2022), both in research and in practice. More and more scientists and engineers are becoming aware of the tremendous potential of CFD, and the fact that the cost of a CFD study is not by definition high. We also observe different levels of CFD. “Basic CFD” is limited to solving the fluid flow field, whereas “advanced CFD”, including, for example, multiple phases and kinetics, unveils another level of potential. Every CFD study requires the necessary skills in fluid mechanics/hydraulics, process engineering and numerical modelling, and one should at all times apply the fundamentals of Good Modelling Practice in this respect (Wicklein et al., 2015). Therefore, CFD is likely to be outsourced, rather than being undertaken in-house within individual utilities.

In an industry setting, we observe increasing demands for CFD in different ways. Traditionally, CFD was used for troubleshooting of systems that had already been built. A first trend is that CFD is now being used as an add-on in the engineering design phase to refine designs based on rules-of-thumb and to avoid unpleasant surprises after construction. This can be referred to as “CFD for model-based design”, which is likely to become mainstream and even standard practice in tenders. A second trend is that technology providers increasingly see the power of CFD to reduce the time-to-market of their technologies and to apply the principle of Quality by Design (QbD). This can be done through “virtual piloting”, thereby (partly) replacing physical pilot studies. Given the CAPEX and OPEX of the latter, CFD can reduce costs and a designer can test many more scenarios. Mostly, these exercises reside in the advanced CFD applications.

In an academic setting, we see the following trends: multiphase approaches are still challenging, especially in WRRF unit processes as they often involve empirical sub-models /functions that need improvement (e.g., unified framework for different sedimentation regimes, flocculation, rheology etc.). In aerated reactors, better prediction of bubbles dynamics is required in order to better assess gas transfer. In this respect, “Population Balance Models” have the potential to capture bubble size distribution. The impact of fluid rheological properties is also of importance. Another opportunity regarding advanced CFD is leading towards a better understanding of the properties of biomass aggregates (flocs/granules/biofilm) in relation to hydrodynamics and especially shear stress. When considering kinetics in combination with CFD, the different components of transport and mixing at different scales can be included: advection (due to the velocity field) but also both molecular and turbulent diffusion. The latter is the most challenging as it requires selection of an appropriate turbulence model and an accurate link between turbulence and transport of scalars. In this context, virtual tracer tests provide a relevant method to assess solute transport and dispersion and to validate models. This validation can also involve other methods: according to the modelling objective, the selection of an appropriate validation method and its level of accuracy must be carefully considered.

In order to build computationally efficient models for dynamic and/or plant-wide modelling, the derivation of compartmental models from CFD analysis is an increasing priority. A “compartmental model is representative of the system geometry and spatial distributions of occurring phenomena” (Jourdan et al., 2019). Typically, compartmental models are used where fluid motion is not affected by other phenomena (e.g., Mixed Liquor Suspended Solids increase over time, affecting density and rheology), and therefore a number of new approaches need to be developed to provide a seamless transition from “full” CFD, through compartmental, to plant-wide simulation.

Uncertainty and risk modelling

In recent years, the use of models as aids in the design and operation of treatment plants has been steadily increasing. In design, mathematical models implemented in simulation software are the first and often the only design method that engineers employ. They are used instead of, or in combination with, conventional heuristic guidelines (e.g. safety factors). During operations, mathematical models are increasingly used for optimisation. In contrast to design guidelines, where uncertainty and variability are accounted for by using safety and peaking factors, process models normally do not incorporate risk evaluation procedures. Therefore, when using simulators to predict energy requirements, resource recovery potential, effluent quality, and environmental risks for a plant with a 30-year design horizon, it is not yet clear how uncertainties linked to climate change, for example, will translate to appropriate design flexibility to meet all the criteria outlined above (Belia and Johnson, 2013). In urban settings, scenario-based exploratory modelling has become widespread, enabling deep uncertainties in future planning to be accounted for by understanding potential transition pathways (Duque et al., 2022; Zischg et al., 2019; Urich et al. 2014).

There is a need, therefore, for the incorporation of risk assessment tools in simulators. This will leverage the power of models and provide methods to quantify uncertainty in designs. Utilities will require such tools as they are starting to move more towards the implementation of risk management, rather than risk avoidance, to bring more value to the people they serve. The increasing cost pressures being felt by utilities, in combination with the ability to quantitatively evaluate process risk, is opening up areas that utilities can take advantage of (Belia et al., 2021). An interesting aspect of this trend is the link between the risk culture in a utility and their ability to take advantage of these new risk management tools.

Research and development agenda

Two main points are currently the focus of the leading-edge MIA agenda:

- **Application of digital twins in the water sector**
  Digital twins are combinations of models that provide a digital representation of a specific part of the water system (e.g., WRRF, sewers, etc.) and utilise real-time data from multiple sources. While promising tools for online decision-making, the development of digital twins lacks a unified approach. Aspects like model complexity, handling of uncertainty and data requirements, among others, need proper assessment to ensure successful application of digital twins. MIA is leading some activities towards the development of consensual guidelines, including the publication of a white paper on digital twins and submitted proposals for organisation of workshops on digitalisation at WRRmod2023, in South Africa, and at the World Water Congress & Exhibition 2022, in Copenhagen, Denmark.
- **Collaboration with other SGs**
  Closer interactions need to be established with other SGs to further strengthen the “integrated” aspect of the MIA SG. This applies both to fields of application (e.g., drinking water and process water technology) and to methodological aspects. A potential way would be to set up joint TGs on specific topics. A concrete example is the launch of a TG on “Modelling of Membrane Processes” (active since 2018). Joint webinars under the umbrella of multiple SGs have also been initiated in 2021 and will continue to develop.

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Nutrient removal and recovery: innovative technologies

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Introduction

The beginnings of biological nutrient removal (BNR) from wastewater date back to the early 1960s for nitrogen (N) and phosphorus (P) removal (Levin and Shapiro, 1965) and the 1970s for combining both N and P removal (Barnard, 1974). Harmful algal blooms, hypoxic conditions, and loss of submerged aquatic vegetation are the results of the accelerated growth of algae and phytoplankton due to higher concentrations of nutrients. Eutrophication poses risks to public health, resulting from direct exposure to waterborne toxins and/or consumption of shellfish contaminated with algal toxins. To combat harmful effects of eutrophication due to excessive loading of nitrogen and phosphorus in the aquatic environment, BNR has emerged as the preferred method worldwide, for nitrogen especially. Over the last decade, BNR has rapidly spread to many parts of developing countries in Asia, South America, and Africa as the most economical and effective method of managing nutrients from wastewater (Steffen, et al., 2015).

Technology-based nutrient limits are now prevalent or being promulgated in Europe and Asia, including more recently in large population centres of China and India. In North America, water quality-based limits prevail, with phosphorus limits being mainly applied to fresh water systems, and nitrogen limits applied to estuarine systems and a combination in a few locations that transition between both systems. The typical design requirements for total nitrogen is 10–15 mg N/L, regardless of the strength of wastewater and of the carbon/nitrogen ratio. More stringent nitrogen limits are applied to sensitive estuarine systems, with limits as low as 3–4 mg N/L for total nitrogen. Ammonia requirements are more variable and are as low as 1 mg N/L or not specified in many cases. Total phosphorus limits are usually between 1–2 mg P/L with much more stringent limits of 0.1–0.2 mg P/L being applied to sensitive water bodies, and as low as 0.05 mg P/L limits applied for very sensitive lakes and rivers in North America.

Existing knowledge

Nutrient management and removal technologies currently in use at point sources, such as wastewater treatment plants (WWTPs), are mainly biological processes for nitrogen removal and mostly chemical processes for phosphorus removal. In addition, biological phosphorus removal or a combination of both biological and chemical removal is also widely used. Nutrient removal systems have successfully been operated in many parts of the world for decades to protect receiving waters against eutrophication. However, those systems have been focused on treating wastewater and disposing of the residuals for complying with effluent standards using extremely conservative design methodologies (typically not designed optimally, thus using more resources, such as electricity and chemicals) (van Loosdrecht and Brdjanovic, 2014). This regulatory compliance-based paradigm began to shift in recent years towards some forms of intensification, often targeting more stringent discharge limits at minimum resources expenditure. As the nutrient removal in traditional biological nutrient removal (BNR) processes is closely entangled with organic carbon, the shift in optimising carbon and energy balances profoundly affects nutrient management. In the future, wastewater treatment facilities may become more environmentally sustainable through (1) maximising removal efficiencies, (2) optimising designs, while (3) conserving significant material and energy resources and (4) minimising CO_2 footprint. Intensified low energy demanding technologies for retaining biomass in bioreactors are brought forward (granular sludge, biofilm carriers, and hybrid systems). The promising paradigm-shift includes also shortcut nitrogen removal processes, i.e. nitrite shunt process (nitritation/denitritation), deammonification (partial nitritation/anammox, PNA) and partial denitrification combined with anammox (PdNA) (Regmi et al., 2015; Lackner et al., 2014).

Recovery and reuse of nutrients from wastewater remain a focus. Although technical solutions for N and P recovery are available, identifying opportunities of nutrient recovery products in a wide range of industrial sectors, not limited to the agriculture or fertiliser market, is needed to provide better economic drivers for such a circular (closed-loop recovery and reuse) approach. Dozens of P recovery approaches have been studied to date (Egle et al., 2016); and current research efforts target the increase of the overall recovered amounts with a particular focus on plants (often the larger ones) that rely on chemical P removal for the potential higher efficiencies. For N recovery in sidestream, almost 50 different physical, chemical and (to some extent) biological techniques have been identified, and most of them produce ammonium sulfate in the form of crystals or liquid solution (Beckinghausen et al., 2020). Nutrient management in alternative streams from source separated urine, food waste, agriculture and aquaculture also deserve more attention.

Nutrient removal and nutrient recovery should not necessarily be considered as alternatives or competitors; both can complement each other in rendering a treatment scheme as resource efficient and low impact as possible. Integrated nutrient management in those facilities should take into consideration economic indicators and overall environmental impacts, such as greenhouse gas (especially nitrous oxide) emissions and carbon footprint; development and application of sustainability metrics, energy efficiency, use of recovered products and chemical usage.

General trends and challenges

Challenges

The main challenges for nutrient removal and recovery efforts are the following:

(1) cost of technologies;
(2) sustainability in the context of meeting low effluent standards;
(3) complexity of the process, process control and availability of skilled labor force;
(4) desired management of greenhouse gas emissions from wastewater nutrient removal facilities;
(5) low value of nutrient recovery products from wastewater facilities;
(6) resiliency and robustness of nutrient management approaches in the context of climate change, meeting low and consistent effluent or product standards.

General technology trends in nutrient management include:

- carbon efficient nutrient removal processes based on a combination of shortcut nitrogen and biological phosphorus removal approaches;
- energy neutrality and carbon footprint management;
- enhanced process control approaches for nutrient management;
- integration of molecular tools within nutrient management;
- phosphorus recovery technologies for integration with chemical P removal.

Carbon-efficient nutrient removal processes

In recent years, research has focused on alternative nitrogen removal strategies that reduce capital, chemical, and energy costs. To achieve these goals, technologies show the following features:

(1) Efficient use of wastewater carbon sent to BNR: this source of carbon is freely available for nutrient removal and can be efficiently used for nitrogen and biological phosphorus removal through optimised aeration control strategies or step feeding wastewater strategically within the BNR system.

(2) Some degree of short-cut nitrogen removal to overcome limitation in wastewater carbon when needed: short-cut nitrogen schemes proposed will contain most likely a combination of conventional nitrification/denitrification and different levels of nitritation/denitritation, nitritation/anammox or partial denitrification/anammox. The degree of short-cut nitrogen removal is driven by carbon availability and should be considered dynamic.

Mainstream shortcut N removal and mainstream deammonification processes represent a paradigm shift for the industry, offering the opportunity for sustainable nitrogen removal, energy neutral or even energy positive facilities and dramatic reductions in treatment costs with widespread environmental benefits. In addition, successful shortcut nitrogen removal applications can allow enhanced carbon recovery while still meeting effluent limits. However, full-scale implementation of mainstream shortcut nitrogen removal, and especially anammox-based shortcut nitrogen removal, has met with limited success (Rahimi et al., 2020). Shortcut N removal systems developed based on the partial denitrification (PdN) route, rather than the NOB (nitrite oxidising bacteria) out-selection route, could provide more reliable nitrite production and could accelerate full-scale implementation of shortcut N technologies. Even though the reaction path for the partial denitrification/anammox (PdNA) route seems longer than nitritation/anammox route, a 50% reduction in aeration (instead of 60%) and 80% reduction in carbon (instead of 100%) was estimated for the PdNA option. Partial denitrification/anammox (PdNA) technologies span a range of readiness levels, with the post polishing attached growth system showing a fast trend towards full-scale application in plants that rely on external carbon dosing (Le et al., 2019; Campolong et al., 2018; Du et al., 2019). Cost reduction of chemical use has become a major driver for shortcut nitrogen removal applications, much more than energy savings.

Energy neutrality and carbon footprint management

With nation- and continent-wide commitments to mitigate climate change in Europe, Australia and other parts of the world, managing the carbon footprint of the plant in addition to treatment goals has become an important objective. Energy balances are mainly controlled by enhancing carbon redirection from wastewater to sludge, and anaerobic digestion of sludge and co-substrates for the direct production of methane (Maktabifard et al., 2020). In addition, choice of aeration equipment and implementation of aeration control strategies have become essential to reduce energy demand for aeration within the biological systems, which typically accounts for about 60% of the total energy consumption. The overall energy balance of the plant is, therefore, closely linked to carbon management and carbon efficient nutrient removal.

The nitrous oxide emissions of full-scale WWTPs form a major uncertainty of the carbon footprint of the plant. Several utilities in Europe have invested in online measurement of nitrous oxide for the past few years. However, the problem is that it is still not easy to distinguish the governing factors in nitrous oxide formation in full scale systems (Gruber et al., 2021). Therefore, true management and reduction of nitrous oxide emissions is not feasible so far. Utilities need novel tools that provide insights in mechanisms of nitrous production under dynamic conditions. The latter could eventually lead to development of mitigation approaches.

Enhanced process control approaches for nutrient management

The cornerstone of shortcut nitrogen removal technologies and energy management lies in recent advances in control strategies enabled by advanced sensors and automation. In fact, advanced aeration control strategies such as ammonia-based aeration control (ABAC) and ammonia and NO^x based control (AvN) have shown to allow for significant savings in aeration energy compared with conventional dissolved oxygen-based control (Regmi et al. 2015). In addition to the key role of process control to manage resources, the more stringent and in some regions (i.e. China) instantaneous nitrogen permits have increased the need for reliable process control to balance operational cost with permit requirements. Furthermore, integration of nutrient management with agricultural water reuse has created new expectations of nutrient removal systems and has created a need for very consistent water quality output. Recent development in data-analytics tools to perform automated diagnostics on online probes, and correct for probe drifting and improve stability of process controllers, deserve more attention to fulfill water quality expectations. In addition, such data driven approaches can lead to the development of better operator tools to inform needed actions and provide early warning systems to avoid permit violations, unwanted greenhouse gas emissions, and/or increased operational cost.

Integration of molecular tools within nutrient management

Microbial communities are the backbone of WWTPs, and biological processes are crucial players in new resource and energy efficient treatment schemes. Compared with conventional systems, robust shortcut N technologies require a higher degree of control to maintain the fine balance between the dominant microbial groups. In this perspective, new molecular tools and approaches to rapidly and cheaply characterise complex communities are needed. The challenge lies in understanding the factors regulating the metabolism of each community member of interest, and their mutual interactions, and translating this understanding into process design and control strategies. Recent years have witnessed enormous advancements in DNA and RNA based methods (Sczyrba et al., 2017). The recovery of complete genomes from metagenomes of complex ecosystems is now state of the art, and the analysis is offered by commercial companies. Based on genomic data, the composition and metabolic potential of a given community, and their dynamics, can be characterised with unprecedented detail. However, metagenomic analysis alone does not provide information on the actual metabolic functions expressed by the dominant microorganisms. To this end, genome-resolved metatranscriptomiccs can be employed to query patterns of gene expression and active populations (e.g. the most active N cycling taxa) (Lawson et al., 2017). Moreover, mass spectrometry base meta-proteomics allows for the simultaneous phylogenetic and functional characterisation of the involved microorganisms, and how their role changes in response to operational or process perturbations (Den Bossche et al., 2021). While the application of meta-proteomics to complex ecosystems, such as engineered microbial bioprocesses, is in its infancy, it is a mature technology and its application in combination with other omics is expected to profoundly change our understanding of WWTP microbiomes in the next years. Omics tools also provide a means to understand and leverage newly discovered or poorly understood functional groups in both N cycling, such as comammox bacteria, and P cycling such as Tetrasphaera. A key need going forward is to develop approaches to not only use meta-omics or other molecular tools for process understanding, but also for process optimisation, development of novel bioprocesses targeting nutrient recovery and, perhaps, even for near real time process control. Advances in rapid DNA sequencing through, for example, MinION sequencing promise rapid advancement towards this goal (Sereika et al., 2021). Looking to the future, enhanced interactions between the NRR and microbial ecology and water engineering (MEWE) community is expected to help address these knowledge gaps.

Phosphorus recovery technologies for integration with chemical P removal

Chemical precipitation of phosphorus is a globally used method in phosphorus removal, and it is an essential process step when low or extreme low concentrations should be achieved. Additionally, it is a relatively stable and adjustable process. The potential of this sector for P recovery was only recently appreciated as, during the last five years, new technologies have been developed targeting chemical P removal plants (Di Capua et a., 2022). Finnish RAVITA of HSY Water Utility (HSY, 2020) and Dutch ViviMag of Wetsus (Wetsus, 2020) are recent examples of new perspective technologies for P recovery. In the case of RAVITA phosphorus is recovered as phosphoric acid and as vivianite in case of ViviMag.

The main idea in the RAVITA process is post-precipitation of P from the water phase at the end of the entire wastewater treatment process and to produce separated chemical sludge (Rossi et al., 2018). Separated chemical sludge is then processed further by dissolution and solvent–solvent extraction steps, resulting in phosphoric acid as the main recovery product.

Alternatively, the ViviMag technology is based on a magnetic separation process, by which the insoluble iron phosphate mineral vivianite is recovered from sewage sludge after anaerobic digestion (Wetsus 2022). During anaerobic digestion Fe(III) is reduced to Fe(II), which results in vivianite formation. The separation relies on the paramagnetic character of the vivianite mineral. Both new technologies are currently in piloting phase and show high P recovery potential (>70% of inlet P). Future testing and research will need to provide insights into product value, ease of operation and overall business case.

Conclusions and research or development agenda

Resource-efficient nutrient removal research and implementation is accelerating in many regions of the world leading to a need for enhanced understanding of the underlying mechanisms to further improve the control of treatment and recovery systems. Process intensification, resource efficiency and sustainability are important features needed in technology developments of the future.

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Innovative technologies as levers of strategic asset management

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Introduction

This paper aims to explain why and how innovative technologies are enablers of strategic asset management (SAM) of water supply, wastewater and storm water systems. Asset Management (AM) in the water sector deals with managing water infrastructures and services in a sustainable way, with intergenerational responsibility, while dealing with performance, risk and cost (Alegre and Coelho, 2012). In a simple way, strategic asset management is about how to act today to protect our children's future. As part of their root objective of delivering potable water, collecting and treating wastewater and draining storm water, water systems are expected to: provide a good quality service for all, at all times; provide efficient and safe infrastructure and services; become more reliable, flexible and resilient; and protect the natural and built environment. On top of that, water systems are faced today with challenges that are drivers for change. These drivers are interconnected and partially overlap each other. Utilities need to address them concurrently and in an integrated way, in particular:

- address the climate change emergency and its expected impact on urban water quality and quantity, on average and under stressful events;
- contribute to meeting the UN SDG and to respecting the human rights to water and sanitation;
- understand the interconnections between water services and public health, and collaborate with related organisations;
- play an effective role in the circular economy, by promoting closed-loop systems and minimising the use of resources and the production of waste, pollution and carbon emissions;
- acknowledge the links in the water-energy-food nexus and the need for an approach to ensure water and food security, sustainable agriculture and energy production under increasing demands (FAO, 2011).

Urban water utilities are assimilating these drivers, steadily incorporating them in their vision and strategic objectives, and gradually addressing them in their strategic asset management (SAM) plans.

These challenges motivate the urban water utilities to evolve towards new standards. However, the bulk of water system assets are expensive to build and are designed to last several decades. Utilities have to deal with a highly valuable but also rather demanding legacy. This infrastructure cannot be replaced, neither as a whole nor as frequently as the pace of evolution the world needs. The path towards these new standards implies managing our existing water systems strategically, by rethinking them, making them evolve from their current state to the desired future configuration. In this process, like-for-like replacement of assets that fail can no longer be the default option. All rehabilitation interventions are opportunities for improvement. If this is the path, complexity in the transition is expected and there is a deep uncertainty associated with change. In fact, innovative technologies are part of the solution. Technology plays an increasing role in all processes of the above referred transition path: planning, redesign, (re-)construction, operations and use. Rethinking existing systems and combining the use of long-lasting assets with modern technology (e.g. for water treatment, for monitoring and for processes control) is the only feasible path towards sustainable and resilient water services.

Key terminology

According to the ISO 55000:2014 standard (ISO, 2014), asset management is the coordinated activity of an organisation to realise value from assets. The realisation of value will normally involve a balancing of costs, risks, opportunities and performance benefits. The term activity can also refer to the application of the elements of the asset management system, and it has a broad meaning and can include, for example, the approach, the planning, the plans and their implementation. An asset is an item, thing or entity that has potential or actual value to an organisation (ISO, 2014). The period from the creation of an asset to the end of its life is the asset life. An organisation may choose to manage its assets as a group, rather than individually, according to its needs, and to achieve additional benefits. Such groupings of assets may be by asset types, asset systems, or asset portfolios.

Given the system behaviour of water infrastructure, where asset interdependencies are central, it is fundamental that asset systems are in the core of the asset management processes of water utilities.

Infrastructure asset management of urban water infrastructures is considered (Alegre and Coelho, 2012) as the set of processes that utilities need to have in place in order to ensure that infrastructure performance corresponds to service targets over time, that risks are adequately managed, and that the corresponding costs, in a lifetime cost perspective, are as low as possible. In the scope of this publication, infrastructure is meant to include all physical assets of the urban water systems, either buried or above ground.

Existing knowledge on the topic

Managing our water systems strategically involves bearing in mind three complementary points of view, all of them addressed in the IWA Lisbon Charter (IWA, 2015) and in the IWA principles for Water Wise Cities (IWA, 2016):

- Public policy: sound public policy provides the enabling environment for water services to implement strategic asset management (Alegre et al., 2019; Batac et al., 2021);
- Regulation: effective regulation of water services is key to foster quality and sustainability of water services (Baptista, 2014);
- Management: skilled management of water services, by utilities, as the ultimate developers of these new standards (Alegre et al, 2013; IAM, 2019; IPWEA, 2015).

Usually, using technology as a lever is associated with management processes. According to Global Water Intelligence (GWI), using technology to support asset management had a potential saving on total expenditure over 5 years (2016-2020) globally for drinking water processes (treatment, distribution, and customer services, metering and billing) of about USD 176 billion, while the potential saving in the waste water sector is about USD 143 billion (GWI, 2016). Savings due to implementing digital solutions in water systems (e.g. for leakage control, remote detection of wastewater discharge or to reinforce consumers engagement) were expected to be between 12% and 18% of present OPEX, slightly higher in treatment than in distribution and collection (Vairavamoorthy, 2019). Nevertheless, technology may also bolster an effective public policy and a supportive regulation, which will then both link to management processes, as either enablers (or barriers) for change.

Public policy

Governments (at national, regional or local level) define their specific goals and, in order to achieve them, they need to establish and implement a public policy regarding assets and resources, maximising their value for society and the environment, in a long-term perspective. In practice, public policies creating an enabling environment for asset management will achieve their goals more efficiently and effectively (Alegre et al., 2019; Batac et al., 2021). Any public policy regarding access to safe and reliable water services should adopt a holistic approach addressing several key building blocks (Baptista, 2014), many of which will benefit from the implementation of innovative technology for their transparency, traceability and accountability. Key building blocks of such public policy include, among others:

- the establishment of strategic sectorial plans;
- developing a legal framework that is understandable, accessible and simple to address by utilities, regarding the asset management systems 'requirements, the corresponding enforcement mechanisms and penalty tools;
- implementing a process that timely allocates financial resources to asset related projects;
- society engagement;
- and information provision in order to ensure transparency and accountability.

These building blocks will be favoured by innovative technology, particularly digital technologies and dependable and secure networks, data repositories and platforms. These technologies offer new opportunities to enhance public policies, informing them with broader and more accurate information, control mechanisms and society participation tools. On the other hand, governments have the duty of enabling an environment open to innovation in strategic asset management, which is crucial in a sector that is traditionally very conservative due to its monopolistic nature, low cost of the services compared with other public services, and long duration of assets.

Promoting the use of existing infrastructure, through a balance between new assets (expansion) and maintenance and rehabilitation of existing assets, will encourage innovation. By rethinking the asset's function, by implementing a strategy advocating re-naturalisation and by promoting asset performance while extending its useful life , innovation can be materialised e.g. by using trenchless techniques, nature-based solutions, new materials or advanced treatment technologies.

Social media and improved channels of communication will contribute to public policies related to community engagement, by creating awareness of asset value, including an intergenerational responsibility perspective, and by raising awareness to individual roles to address collective challenges (Vairavamoorthy, 2019), e.g., citizens are most likely to adjust consumption behaviours if alerted that a drought is about to happen and to rethink their disposal into the storm water system if they are aware of its final destination. Co-decision is also becoming more and more an element on public policies. Intergenerational responsibility needs to be present all time in decision making in order to justify investments which effects are only directly perceived in the medium and long term.

Regulation

Regulation will benefit from access to reliable information and to sharing that information, and this also requires digital technologies, dependable and secure networks and data repositories, as well as data integration, analytics and visualisation. Given the territorial scope, evolving from paper to digital maps, recurring to intelligent information systems, is basic. Besides benchmarking opportunities for utilities, providing showcases of best practice also enhances synergies and competition. Likewise, disclosure of service quality also promotes stakeholder engagement, that in return will be more eager to feedback to the regulator with their opinions on water services. For such, transforming the citizen interaction model across the web, using networks, social media or apps in mobile devices might ensure an effective and meaningful exchange of information.

Management

Closing the loop in urban waters (by rain water harvesting, treated wastewater use, resource recovery, implementation of nature based solutions) means that the frontier between water supply systems, wastewater systems, storm water systems and urban landscape is ever more tenuous. This implies the need for new technological solutions but also new governance solutions, as this poses a challenge for asset management and for the security of these networks. Asset security also has to be monitored and controlled. Likewise, the multiplication of prosumers (producer and consumer that reuses water in a home environment; Kotler, 2010) in urban areas poses an increased risk because there are aspects beyond the control of the utilities. The massive use of low cost microsensors, preferably online, could be positioned as a part of the solution (e.g. temperature, turbidity, on/off status). Microsensors are cost-effective, miniaturised and highly sensitive for on-site detection and online monitoring of water related variables (Xia et al., 2017),

Climate change has to be thought of by water utilities from several perspectives. Changes in water quality in lakes, reservoirs and urban streams, due to prolonged droughts, reduced water height in rivers that receive wastewater treatment plant discharges (designed for a given receiving waters quality and flow that may be compromised), increased flooding, combined sewer overflows or untreated wastewater discharge and the need to find alternative water sources are some of the examples. Addressing this multiscale, multi-sectorial and multi-hazard challenge, along with the interdependencies and cascading effects between urban services, can be achieved either by a detailed approach via the use of coupled or integrated models, or by using holistic and more general tools. Either way, satellite information (to supply hydraulic and hydrological water data), meteorological models and geographical data are of uppermost importance, preferably gathering massive data from low cost sensors, from small satellite clouds or for group intelligence (e.g. for massive span and redundancy, in large covered areas). Alongside, data science will have a job to perform on this.

Even though there is a tendency for cities to become larger, some parts of the urban water processes might be decentralised. The multiplication of prosumers also contributes to decentralisation. Technology might help to ensure security, effectiveness, efficiency and governance of these solutions, that involve many more actors, scattered in the urban area.

Operation and maintenance might greatly benefit from technological development. The use of micro turbines is an idea for sensor autonomy. Applying autonomous inspection robots or drones to inspect big pipes or water reservoirs might greatly contribute to widen and deepen condition assessment.

Stakeholder involvement is also pertinent for utilities, as costumers that know the system better are more likely to feedback on anomalies or to understand the consequences of an intervention (e.g. to accept pressure drops if warned that a conduit reparation is taking place in the neighbourhood and to accept fair tariffs). It is being recognised that for successful implementation of AM, the work must be done in co-creation, inside an organisation and between organisations. All these sorts of involvement, as previously mentioned, can be enhanced by citizen interaction models across the web.

System design might benefit from large and public datasets (topography, population or hydrological data) for preliminary design and simulation models.

General trends and challenges

Infrastructure asset management needs innovative technology and sets many processes in motion that trigger the need for ingenious solutions. Public policy, regulation and asset management will greatly benefit from digital technologies, networks, social media and data repositories. Asset resilience (robustness, reliability, flexibility) will be enhanced by new materials, alternative rehabilitation techniques and advanced treatment technologies. Operation and maintenance will benefit from massive sensing, online data transmission, intelligent information systems, modelling and data science.

Many of these challenges are mostly associated with developed regions, which might be a misjudgement. Specific technological challenges arise in developing countries, where often service accessibility and continuity face considerable constraints and inventive, creative and tailored solutions for urban areas with limited resources have to be thought of. Developing regions offer many distinctive opportunities and might be a vast market for technology innovation and digital water.

This path has to be travelled by qualified, resourceful and open-minded human resources. Training and capacity building of these people is a challenge to be addressed. Digital tools have been shifting power to the people (Vairavamoorthy and Sarni, 2018).

Conclusions and development agenda

For strategic asset management, technology innovation is not an objective, but it surely is a means to better achieve SAM objectives. Innovative technology will contribute to better knowledge of our systems and our utilities; to assist decision-making; to better decision implementation; and to monitor the effects of decision implementation.

The focus of the IWA SAM Specialist Group (SAM-SG) has been in research, advances and leading-edge practices and communication in AM, and this will continue. Our bi-annual conference, LESAM, has traditionally been assigned for presentations, discussions and knowledge exchange on this overarching topic.

We currently also recognise that countries need to have sound public policies that enable asset management; members of the SAM-SG are actively participating in the identification of the elements that public policy should consider, and on how this links to asset management.

Water governance, regulation and utility management was addressed in the International Strategic Asset Management Forum, that took place in November 2021 in Belgrade, Serbia, focusing on resilience and climate change, sound public policy and long-term planning, and the topic continues to be on the SAM-SG agenda for future events.

We have also recognised that for successful implementation of AM, the work must be done in co-creation, so we aim to demonstrate how co-creation, inside an organisation and between organisations, can be used as a facilitator to create common AM goals. In the 2022 World Water Congress and Exhibition, in Copenhagen, Denmark, we plan to address this issue.

The impact of fuzzier borders among urban water systems and the circular economy concerns for SAM was be addressed in the International Conference on Rethinking treatment with Asset Management in 2021, in Oporto, Portugal.

The next LESAM will occur in May 2022 in Bordeaux, France. Topics on the links between innovative technology, water smartness, circular economy, water cycle fuzzier borders, capacity building and asset management will be addressed and discussed.

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Wetland systems for water pollution control

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Introduction

Treatment Wetlands (TWs) are ecologically engineered systems that remove pollutants from water by harnessing and enriching the physical, chemical, and biological processes that occur in nature. TWs belong to the broader category of Nature-based Solutions (NBS) for water treatment. Treatment wetlands can be used to treat wastewater, contaminated ground water, sewage sludge, industrial waste streams, and diffuse pollution in urban, peri-urban and rural areas and have been successfully used for decades to treat wastewater in both developed and developing countries (Kadlec and Wallace, 2009).

Treatment wetlands can be integrated into the local environment and can provide many additional ecosystem services beyond water quality improvement including, but not limited to, rainwater retention, flood alleviation, increased biodiversity, reduced stress on local water resources, lower energy demands for buildings, increased food production, and creation of recreational areas. TWs can also contribute to the creation of a circular water economy. Cities that want to become more climate-resilient are making it a top priority to increase investments in NBS such as TWs in order to address the social, economic, and environmental challenges they are facing.

Treatment wetlands are energy-efficient, robust, and can be built in a modular approach according to population dynamics and future projected needs. They require simpler operations and maintenance than conventional wastewater treatment technologies, making them practical and affordable to build anywhere in the world, particularly for small communities (fewer than 5,000 inhabitants) in developing countries. This, combined with the other value-added benefits that they provide, make treatment wetland technology well-suited for addressing water and wastewater challenges in the developing world.

Key terminology

A treatment wetland typically consists of an earthen basin filled with water (Figure 1.11a; Free Water Surface (FWS) treatment wetland), sand, or gravel (Figure 1.11b; Subsurface Flow treatment wetland) that is planted with vegetation. Contaminated water flows through the wetland either horizontally or vertically. An impervious synthetic liner or clay layer contains the wastewater while it is being treated. Treatment wetlands can be constructed from locally available materials and generally require less complex operations and maintenance than conventional wastewater treatment technologies, making them practical and affordable to build anywhere in the world, particularly in developing countries (Mara, 2003).

Existing knowledge on wetland systems for water pollution control

The members of the IWA Specialist Group on Wetland Systems for Water Pollution Control are internationally recognised leaders in treatment wetland research and implementation. The Specialist Group has recently published the state-of-the-art of treatment wetlands in an open-access textbook and a new scientific and technical report (STR). The textbook is part of IWA's Biological Wastewater Treatment Series and aims to mainstream the use of treatment wetland technology in the field of biological wastewater treatment (Dotro et al., 2017). The textbook promotes the worldwide dissemination of general knowledge on treatment wetland design, functioning, implementation and sustainable operations and maintenance. The target audience for the textbook is bachelor-level students with a basic knowledge of biological wastewater treatment, as well as practitioners seeking general information on the use of treatment wetlands. The STR focusses on practical information relating to the design and application of treatment wetlands

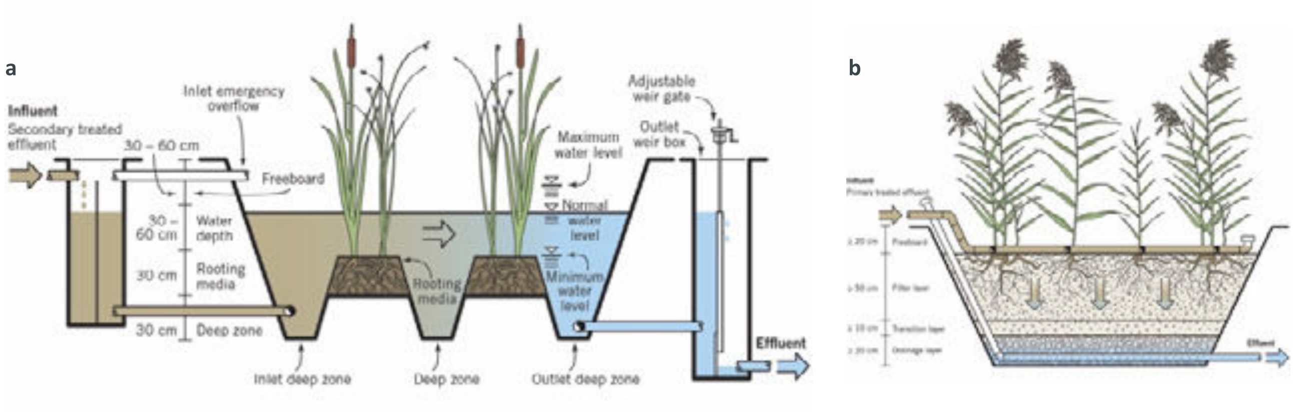

Figure 1.11 Technical schematics of a (a) Free Water Surface treatment wetland and (b) Subsurface Flow treatment wetland (Dotro et al., 2017).

and contains contributions from 60 treatment wetland experts from 20 countries (Langergraber et al., 2019). The primary audience for the STR is graduate-level students (MS and PhD) and design engineers. The STR may also be of interest to secondary groups such as decision-makers and people from non-water technical backgrounds who have an interest in treatment wetland technology and its potential. Members of this IWA Specialist Group have also recently authored textbooks on specific types of treatment wetland designs and applications, including horizontal flow (HF) wetlands (Vymazal and Kröpfelová, 2008), vertical flow (VF) wetlands (Stefanakis et al., 2014), and wetlands for treatment of industrial wastewater (Stefanakis, 2018) as well as stormwater and variable flows (Tondera et al., 2018). The former Chair and Secretary of the Specialist Group have published a review on treatment wetlands in decentralised approaches for linking sanitation to energy and food security (Langergraber and Masi, 2018).

General trends and challenges

Integration into local water cycles

There is an increasing recognition that all aspects of water supply and treatment systems are interconnected. This realisation marks a distinct paradigm shift from discrete, one-dimensional projects to a systematic integration and assessment of all possible ecosystem services, including both tangible and non-tangible benefits and costs. Treatment wetlands have a large potential to contribute to circular economy approaches (Masi et al., 2018) and the Food-Water-Energy Nexus (Avellán and Gremillion, 2019). Many of our IWA Specialist Group members are contributing to the development of evidence-based guidance that assesses the technical feasibility and practicality of NBS for sanitation (including treatment wetlands) in diverse local and cultural context via the Science for Nature and People Partnership (SNAPP; https://snappartnership.net/teams/water-sanitation-and-nature/). Our Specialist Group members also contribute treatment wetland expertise to a recent COST action (implementing nature-based solutions for creating a resourceful circular city; https://circular-city.eu/), which brings together experts from architecture, engineering, biology, and agronomy to find new and innovative approaches for management of local water cycles.

Process understanding

Microbial biofilms are responsible for many pollutant removal processes in treatment wetlands. Despite the amount of research conducted to date, there is still a need to better understand microbiological aspects of pollutant removal in treatment wetlands. Recent research on microbiology in treatment wetlands focusses on identifying microbial function (Lv et al., 2017a; Lv et al., 2017b; Zhang et al., 2018), microbial dynamics over time (Weber and Legge, 2011), selection of specific microbial populations (Hou et al., 2018; Martinez et al., 2018), and response of microbial communities to external factors (Weber et al., 2011; Button et al., 2016).

Process-based models for treatment wetlands aim to provide a better understanding of internal removal mechanisms (Samsó and Garcia, 2013; Langergraber, 2017; Boano et al., 2018; Marti et al., 2018). Calibration is best conducted on full scale systems, and the definition of a good balance between model complexity and user-friendliness is important to promote the use of these models by design engineers (Meyer et al., 2015). Process-based models for intensified treatment wetland designs are also currently under development (Boog et al., 2019). It is expected that treatment wetland models will be refined and further developed in the future.

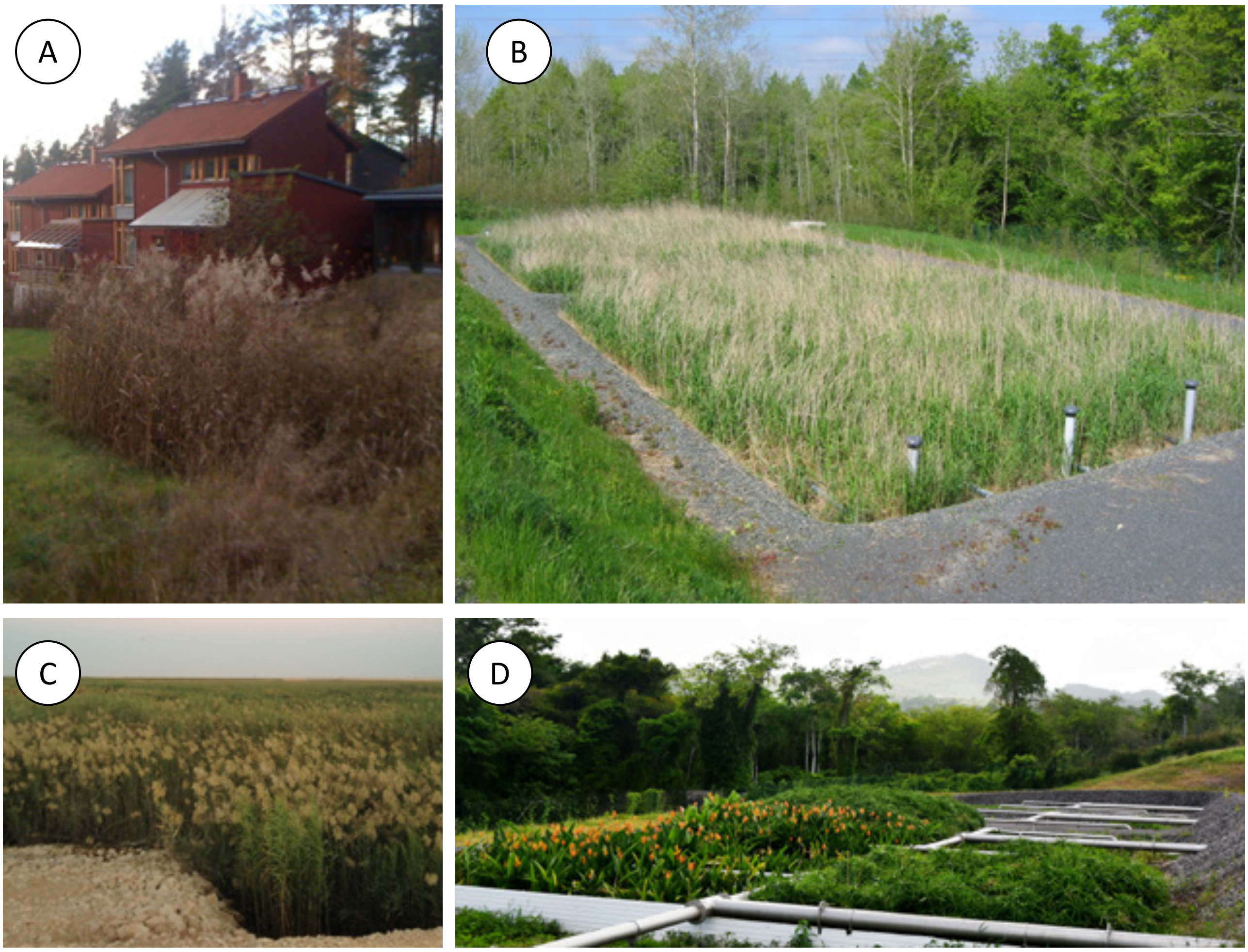

Figure 1.12 Application of treatment wetland systems in different climates: A: cold climate (greywater), B: temperate climate (domestic wastewater), C: arid climate (industrial wastewater treatment from oil industry); D: tropical climate (domestic wastewater). Photo credit A, B, C: Florent Chazarenc; Photo credit D: Rémi Lombard-Latune.

Technology adaptations

Treatment wetland technology has expanded over the past decades from completely passive systems to moderately engineered wetlands, often referred to as intensified wetlands. Across the treatment wetland technology gradient from passive to intensified systems, there are trade-offs between system footprint and energy requirement. A decrease in footprint typically comes at a cost of increased electricity consumption and more complex design and operational requirements. The trade-off is that intensified wetlands are able to degrade pollutants 10- to 1000-fold faster than completely passive wetland systems. Although some intensified solutions have been already successfully applied at full scale (for example, aerated wetlands and fill-and-drain wetlands), intensification is still an open topic which will continue to develop in the coming years. Intensification also applies to bio-electrochemical technology merged with wetland technology, whereby electroactive bacteria, plants and wastewater interact to improve treatment efficacy or generate electricity during treatment (Ramírez-Vargas et al., 2018). Engineering innovations continually overcome technological limitations, as evidenced by the use of super-oxygenation and bioaugmentation to sustain nitrification in low temperatures (Austin et al., 2019). Other technology adaptations aim to take the best aspects of multiple treatment wetland designs and combine them into new, more efficient, hybrid designs (Troesch et al., 2018; Park et al., 2019).

Special efforts are also being made to adapt and apply treatment wetland technology in a variety of extreme conditions, including hot and arid climates (Stefanakis et al., 2018; Nivala et al., 2019a), cold and arid climates (Khurelbaatar et al., 2017; Wang et al., 2017) , and tropical climates (Manjate et al., 2015; Lombard-Latune et al., 2018). Examples of treatment wetlands in various climate conditions are shown in Figure 1.12.

Contaminants of emerging concern

The first research studies on micropollutant removal by treatment wetlands started over ten years ago in Spain (Matamoros et al., 2007). Since then, many lab-scale studies (for example, Lv et al., 2016; Auvinen et al., 2017; Chen et al., 2017; Zhang et al., 2017) and a few full-scale studies (Ávila et al., 2015; Matamoros et al., 2017; Vymazal et al., 2017; Tondera et al., 2019) on micropollutant removal in treatment wetlands have been published. In order to truly further the understanding of how micropollutants are removed in treatment wetlands and what effects design and operational parameters have on removal processes, year-round research studies on different full-scale wetland designs treating real wastewater are needed (Vymazal et al., 2017).

Treatment wetlands are capable of removing organic Prioirty Substances (PSs), substances with Environmental Quality Standards (EQS), as well as Contaminants of Emerging Concern (Gorito et al., 2017), but the substances in current wetland studies do not cover all contaminants listed, for example, in current EU legislation. Treatment wetland removal rates for micropollutants are similar to or sometimes better than those observed in conventional (activated sludge) technologies, with significant improvement observed in intensified treatment wetlands (Nivala et al., 2019b). Recent studies have begun to explore the use of bioanalytical tools for quantifying the effects of all chemicals (known and unknown) acting together in a water sample, even when the individual chemicals are below the limit of detection (Nivala et al., 2018).

New applications

The upper limit on the size of municipal wastewater treatment wetlands is larger than previously thought. Masi et al. (2017) report the successful design, construction and implementation of a wetland for treating wastewater from a community of 20,000 inhabitants in Moldova. Application of wetlands for treating new industrial waste streams is on the rise, with the technology being successfully demonstrated for treatment of wastewater from a glass manufacturing industry (Gholipour et al., 2020), removal of microplastics from stormwater (Ziajahromi et al., 2019), removal of antibiotic resistant genes from sewage sludge (Ma et al., 2020), and treatment of cooling tower water (Wagner et al., 2020).

Future perspectives

Treatment wetlands have an important role in emerging and new approaches to water management because they can contribute to closing local water cycles and working towards a circular economy. The increased application of treatment wetlands for treatment and local reuse of a range of polluted water sources will require different approaches to design. There will be an increasing need for treatment wetland designs to integrate seamlessly into urban environments where space is often limited, and water treatment occurs in close proximity to where it is used. In the future, treatment wetlands will gain increasing use for large-scale groundwater recharge and nutrient reduction for indirect potable reuse, as well greywater treatment, rainwater treatment and storage, and treatment of combined sewer overflows in urban areas.

Future research on treatment wetlands will involve sophisticated analytical methods for target and non-target chemical analysis as well as simpler proxy methods that enable cost-effective water quality screening for large numbers of treatment systems. Monitoring will move from uncontrolled to intensive, with online sensors and robust monitoring tools that will enable the early detection of operational problems such as clogging, reduced hydraulic performance, disruptions in water quality, and maintenance of mechanical components. Operations and maintenance of treatment wetland systems in the future will rely more on remote operational control, especially in situations where the reuse purpose dictates effluent quality requirements. Moving forward, the IWA Specialist Group on Wetland Systems for Water Pollution Control will make a collective effort to advance the knowledge, understanding, and development of treatment wetland technology through long-term data collection efforts on full-scale treatment wetland systems, increased transparency in publication of results, and improved accessibility of useful monitoring data.

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Water and health

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Assessment and control of hazardous substances – global trend of micropollutants in water

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Introduction

In recent decades, plenty of emerging contaminants have been detected at trace concentrations in the water environment. These micropollutants are present in water mainly because of the large amounts of substances manufactured, used or improperly disposed of, as well as the persistence of the chemicals or degradation products during long-distance transport and transformation processes. Several review articles revealed that hundreds of micropollutants and their degradation products have been identified in water environment (Gavrilescu et al., 2015; Geissen et al., 2015; Ebele et al., 2017; Gogoi et al., 2018). The sources and pathways of these micropollutants mostly relate to wastewater discharges from agricultural, domestic, or industrial activities.

Emerging micropollutants such as microplastics and antibiotic resistance have arisen as the focus of research in recent years. Efficient micropollutants management has also been a hot topic which has caught a lot of attention and discussion among the scientific communities, government officials and industrial partners. The trend report drafted by IWA ACHSW SG summarises the existing knowledges for the emerging micropollutants in the world and identifies the trends and challenges. The management strategies for micropollutants and associated regulation and policy are also discussed in this report.

Microplastics in the environment

Owing to its resistance to degradation, microplastics (MP) can be detected in all media such as air, surface and groundwater, in soils, sediments, coral reefs, in the deep sea, biota and even in some foods (drinking water, shellfish, honey, salt and beer). Both macroplastics and microplastics might pose a risk to organisms in the natural environment, for example, through ingestion or entanglement in the plastic. This leads to considerable concern about a direct or indirect effect from the presence of MP in food and the environment. In this section, the basic problems in the assessment of MP particles is presented and data on exposure and effects and preliminary risk considerations are summarised.

Key terminology

One of the core problems in the discussions about MP is the fact, that it is not clear, which particle size are included in the term “microplastics”. Only the upper limit seems to be agreed and is mostly 5 mm sometimes 1 mm. However, the lower limit of the particle size has not yet been sufficiently defined, making the study results very difficult to assign, hardly comparable and poorly suited for risk assessment. According to the definition of the European Food Safety Agency (EFSA 2016), MP have a size of 0.1 to 5,000 micrometres (µm). Nanoplastics measure between 0.001 and 0.1 µm (1 to 100 nanometres). In the current restriction proposal by the European Chemicals Agency (ECHA) for MP as product additives (ECHA 2019) the size range of microplastics is expanded to 1 nm to 5 mm. Nevertheless, there is currently no analytical method that can quantitatively measure such a wide variety of substances and size ranges from micro- to nanoplastic in environmental samples.

Existing knowledge on microplastics

Although there are different standardisation efforts, currently most of the methods for sampling, sample pretreatment, plastic identification and quantification for microplastics in environmental samples are in the development and test stages. For a risk assessment, information on numbers, size, structure, material composition and contamination will be required. The quantitative determination of microplastics is currently carried out using (1) thermoanalytical methods that determine a total content in milligrams of plastic per kilogram or litre or (2) spectroscopic methods (Raman spectroscopy and FT-IR spectroscopy (Fourier transform infrared)) that determine the number of particles of individual plastics in pieces per kilogram or litre and the particle size and in the spectroscopic processes.

An estimate of the sources of MP in Europe shows that the abrasion of tires and road markings, loss of plastic pellets before production and the washing of synthetic textiles are the main sources of MP emissions into the environment (Hann et al. 2018). Koelmans et al. (2019) examined 50 studies; only four received a positive rating for all proposed quality criteria. The MP concentrations, expressed as the number of particles, spanned a total of ten orders of magnitude (1×10^{-2} to 10^8 particles/m³) depending on the individual sample and water type. In surface waters, MP concentrations >300 µm cover a wide concentration range; about 1×10^{-3} to 10 particles / L; for tap water (range 1×10^{-4} to 100 particles/L) higher numbers are often measured because very often particles from 1 µm or from 100 µm are detected. As studies often do not specify sizes or numbers of different size classes the interpretation of the studies and comparability is impossible.

Organisms are exposed to MP through food intake (including filtration, active grazing, and sediment intake) and through the gills (aeration). The uptake, enrichment and excretion and effect of MP depend on the particle size. The risk result is based on the number and type of particles (e.g. polymer type, size, shape and age), but also on impurities associated with the plastic and the size, physiology and life history of the organism. MP particles can be found in the guts of many species. But only particles < 1–3 µm can be uptaken into the blood. In the laboratory, lethal effects could be observed primarily by small particle sizes (<1 µm) (GESAMP 2016).

Preliminary risk assessment showed that MP contamination does not pose an immediate risk to either sea or surface water and that the MP problem in oceans appears to be mainly limited to “hot spots” (Everaert et al. 2018; Burns and Boxall, 2018; Adam et al., 2019, EFSA, 2016). However, according to UNEP and ECHA (2019), with regard to the precautionary approach in the case of marine plastics and MP, measures shall be taken.

General trends and challenges

A standardised procedure is urgently required in particular for small microplastics (<1 mm) and relevant size classes. Environmental concentrations and effects need to be allocated to particle sizes, possibly shapes, materials and impurities. It should be remembered that the volume of 1 particle of 500 µm equals the volume of 10^6 particles of 5 µm. Compared with laboratory tests, there is very little direct evidence of the physical effects of MP in nature (GESAMP 2016). Unfortunately, such data are hardly available in literature. Therefore, further research on wild animals is necessary to improve the data situation.

Antibiotic resistance control in water

Antibiotic resistant pathogens have rapidly emerged and the progress in molecular biology has revealed a high diversity of antibiotic resistance genes (ARGs) and a quite complex ARG transfer. Antibiotic resistance has been recognised as a severe health risk to human beings, as their spread is increasing the difficulty of bacterial infection treatments. This section summarises current findings about the occurrence of antibiotic resistance in aquatic environments. The importance of antibiotic resistance control is then be demonstrated. Finally, the research and development needs are identified.

Key terminology

Antibiotics are a group of medicals used clinically in human and animal therapy for treating the infection associated diseases. Antibiotics are normally incapable to inhibit all of the microbial community, so there are survival bacteria which are resistant to the inhibition and termed as antibiotic resistant bacteria (ARB). The existence of antibiotic resistance genes (ARGs) refers to the genes carried by the survived bacterial cells which can encode resistance to the antibiotics (Levy and Marshall, 2004).

Antibiotics have been intensively used as human medicines, chemical therapy agents, and veterinary growth promoters (Jiang et al., 2013). Large amounts of antibiotics are continuously released into the environment due to incomplete metabolism, promoting the development ARB and ARGs in the water environment (Bouki et al., 2013). The presence of ARB/ARGs has been widely reported in various water systems, posing serious concern to public health. Wastewater, particularly that from hospitals and slaughterhouses, plays a special role when treated in wastewater treatment plants (WWTPs), where the presence of pathogenic microbes create favorable conditions for the transfer of ARGs and proliferation of antibiotic resistant bacteria (ARB).

Current situation on ARG and its control

The issue of antibiotic resistance has been recognised as a major health concern in the 21st century by the G8 science ministers in 2013, as it causes massive loss in both human lives and economy. According to the European Centre for Disease Prevention and Control, 25,000 people die each year due to the infection by ARB. In North America, methicillin-resistant *Staphylococcus aureus* (MRSA), one of the most dangerous clinical ARB, is associated with approximately 90,000 infections and 19,000 deaths annually. In terms of the economic loss, ARB result in massive extra healthcare costs and productivity losses of at least 1.5 billion Euros each year in Europe.

The selective pressure of antibiotics and existence of ARB and (ARGs) are the two major driving forces to develop antibiotic resistance (Kümmerer 2009). The ability of wastewater treatment plants (WWTPs) on the degradation of antibiotics has been reported to be limited (Watkinson et al. 2009, Michael et al. 2013). The remaining antibiotics in the WWTP effluents are thus discharged into surface water. ARB and ARGs have been frequently detected in WWTPs, surface water, and even drinking water with high abundance and diversity (Yuan et al. 2015; Shi et al., 2013; Zheng et al. 2017 and Liu et al., 2018). Therefore, antibiotic resistance in aquatic environments have attracted tremendous concern about their potential health impact.

General trends and challenges

To effectively control the dissemination of antibiotic resistance, deactivation of ARGs is required. It is believed that disinfection processes may be able to play some roles in terms of controlling antibiotic resistance dissemination. Therefore, the impact of disinfection processes on the deactivation of ARGs has drawn the attention of numerous researchers. Among all the disinfection methods, UV irradiation and free chlorine are of the greatest interest as they are the most widely used disinfectants (Pang et al, 2016; Yoon et al., 2017; Yuan et al., 2015; Zheng et al., 2017). Besides disinfection technologies, a few researchers attempted to use other technologies including construction wetland, and advanced oxidation processes to remove ARGs (Huang et al., 2015; Zhang et al., 2016). The deactivation of antibiotic resistance is of great importance in safeguarding the public health and thus is valuable for water industry to develop the cost-effective solutions.

Although metagenomic sequencing and fluorescence-activated cell sorting have identified the main species responsible for ABR, nevertheless there are still open questions such as a lack of standard monitoring targets and agreed threshold values, and also the lack of a standardised protocol for determining ARG removal in wastewater treatments for practical application (Nguyen et al., 2021). Finally, targets need to be based on a risk assessment for future mitigation measures of AMR.

Research and development agenda

The existence of antibiotic resistance in water environment post a great challenge for public health. The effectiveness of disinfection processes on the control of antibiotic resistance dissemination is, therefore, crucial to address the issue of antibiotic resistance. Controlling of ARB/ARGs is not straightforward, even when the bacteria carrying ARGs have been inactivated, DNA released from the cell may persist in certain environment compositions. ARGs are thus considered as emerging contaminants (Pruden et al., 2006). More research and development work in this field are currently needed to provide an in-depth understanding which could serve as a basis for technology advancement. Effective ARB/ARGs control strategies are urgently needed.

Management of micropollutants in water environment

In general, chemical and biological pollutants can be collected and treated in wastewater treatment systems, in this way their releases into the receiving water can be reduced. Owing to their particular chemical and biological properties, however, these micropollutants may have to be treated differently from the conventional wastewater treatment processes. Plenty of literatures were published which discuss the issue of advanced treatment techniques and removals of micropollutants in the wastewater treatment plants and occurrences of these contaminants in surface and ground water. However, due to the lack of knowledge concerning the characteristics and fate of many contaminants in treatment processes, it is thus important to take integral actions to address emerging contaminant-derived problems and to prevent potential hazards to ecosystems and human health. The fate of micropollutants in water environment is of particular concern, as human beings are continuously exposed to these contaminants, which may cause potential adverse health effects. In addition, the problem is more complicated when the concentrations of these contaminants in water are very low.

Risk assessment of chronical exposures to low levels of micropollutants in water

The main objective of the risk assessment is to protect the aqueous ecosystem and human health. Owing to the lack of exposure data and toxicity information, the health risk assessment for human being is currently not available for most of the micropollutants. The ecosystem risk assessment of a micropollutant is even more challenging. In general, the processes for assessing the ecological risk of a chemical substance include two steps: obtain the concentration of the chemical in an environmental medium (predicted environmental concentration, PEC) and define its concentration which will not cause adverse effect on the target organism (predicted no effect concentration, PNEC). It is assumed that no negative effects will occur when PNC is less than PNEC. However, it is difficult to obtain the appropriate PNEC value for a variety of micropollutants (Geissen et al., 2015).

To address the adverse impacts of micropollutants on ecosystems, it is essential to identify the micropollutants present in the water environment and to elucidate the characteristics and fate of these contaminants in water environment (Gavrilescu et al., 2015). Chemical analysis has improved greatly through the development of high-resolution mass spectrometry (HR-MS). Multi-analyte methods are developed that can cover a great range of target chemicals. From lists with chemicals that are suspected to occur in environmental samples, a suspect screening can be performed to obtain a semiquantitative analysis. Moreover, a non-target approach allows to detect a high numbers of “features” (accurate molecular masses associated with unknown chemicals). Databases and suspect lists are accessible online and provide an important data source to elucidate unknown compounds (Escher et al. 2020). All these new developments allow to detect more and more chemicals in the environment, but still leave out undetected compounds or features that cannot be identified. The sensitivity of instruments is increasing, but often a cleanup or enrichment of environmental samples with complex matrix is necessary to detect compounds occurring at low concentrations. Such procedures are time-consuming and may lead to losses of compounds of interest. Moreover, degradation products are largely unknown and not included in database, leaving them difficult to identify.

The utilisation of cell-based in vitro methods would allow the integrated assessment of different adverse effects in whole samples. With the development of high-throughput methods, more samples can be tested and an acceleration of risk assessment can be expected (Escher et al. 2020). Recent research shows that chemicals with the same mode of toxic action tend to follow the mixture concept of “concentration addition”, and bioanalytical equivalent concentrations (BEQbio) are calculated, which relate the toxicity of a mixture to one chemical for a specific mode of action. For example, estradiol equivalent concentrations are used for assays addressing endocrine disruption. Based on acceptable BEQbio, effect-based trigger values are derived and proposed to be included in future regulations (Brack et al., 2019). A prioritisation approach is important for comparing the possible hazards of different chemicals and their degradation products and for the quantification of the effects of chemical mixtures on human health and ecological risks and the assessment methods developed can be used to assess the cumulative risks associated with exposure to multi-contaminants. High-resolution mass spectrometry should be complemented with bioanalytical tools in common monitoring studies to elucidate problematic chemicals or chemical mixtures (Escher et al., 2020).

Environmental regulations related to micropollutants

The management of micropollutants in water resources is an important issue, especially in vulnerable ecosystems. It is essential to establish a comprehensive management framework, with consideration of the source, transport, transformation, and fate of micropollutants for their effective management. The numerous micropollutants in water make it difficult for authorities to effectively control their production and uses and to manage the widespread of micropollutants in the environment (Gogoi et al., 2018). To date, there is still a lack of relevant regulations to limit the discharge of these contaminants from treated wastewater effluents or to regulate the water quality standards of these contaminants in drinking water and environmental waters.

There are several management strategies adopted to manage these contaminants in water (Gogoi et al., 2018), here are some examples:

1. In order to avoid the potential impact of micropollutants on human and biological systems, USA, European Union (EU) and several other countries focuse on reducing the use of chemicals added in consumer and daily use products, as well as limit the use of chemicals in personal care products. Although several contaminants have been included in the Contaminant Candidate List for assessment, however, currently no standards have been set for regulations of these emerging contaminants in drinking water.

2. The EU Water Framework Directive developed environmental quality standards (EQS) for a list of priority substances (33 plus 8), which was adopted in 2008 (EC, 2008) and revised in 2013 (EC, 2013); at this point, 12 substances were added. Those substances which were identified as priority hazardous substances are subject to cessation and will be phased out in cooperation with the European Chemical Agency (ECHA) within 20 years. In addition in 2013 a watch list was implemented of substances subject to later review.

3. Switzerland has taken a leading role in preventing the discharge of micropollutants from wastewater treatment plants by implementing on January 2016 a new Swiss Water Protection (Eggen et al., 2014). Here, an upgrade of wastewater treatment is required to eliminate micropollutants by 80% in selected wastewater treatment plants until 2040, treating the wastewater of about 70% of the Swiss inhabitants. Other places or regions have voluntarily implemented advanced wastewater treatment to protect the aquatic ecosystem (Rizzo et al., 2019).

Challenges for water resources management and policy

There are some issues that need to be resolved so that strategies for integrated management of micropollutants in water environment can be proposed (Naidu et al., 2016; STAP, 2012), which are as follows:

1. Information related to the chemical properties of micropollutants

Identification and assessment of micropollutants in different environmental media can be challenging. New chemicals are constantly being manufactured and releases into environment as a result of the development of new consumer products and new production processes, making it necessary to assess whether these new chemicals are chemicals of concerns or not.

2. Needs for management regulations

Fast economic developments and breakthroughs in industrial technologies have gone beyond existing regulatory practices and procedures to effectively control the releases of micropollutants into environment. Although there has been some progress in regulations, there are still needs to elucidate the interactions between contaminants and the environment and ecological units of natural water. Information concerning the sources and distributions of contaminants in the environment and their physical and chemical properties can then be used as basis of enforceable management systems.

3. Importance of source control for releases of micropollutants into the environment

There are several ways to effectively reduce the discharges of micropollutants into the environment, which include: improve treatment processes and use of green chemicals, reduce manufacture and use of chemicals of concern, reduce wastes, environmental friendly disposal of wastes, adopt stricter standards for discharges of contaminants in treated wastewater and so on (Gogoi et al., 2018;). The upgrade of wastewater treatment systems to fulfill the stricter discharge standards is a major challenge, as it requires investment to improve the existing facilities, but is feasible as the example of Switzerland shows.

4. Improvement of monitoring systems

Detection, identification and quantitation of micropollutants and their degradation products in different environmental media are essential to understand their origins and fates. This is challenging because, despite better analytical tools, there are a large number of unknown micropollutants and related degradation products. Information about the source, fate, and potential hazards of contaminants changes over time due to changes in the production, use, and disposal of these chemicals.

Conclusions

Nowadays more and more emerging micropollutants have been identified in the environment. It is clear that environmental contamination with plastic poses a big problem for many species and the environment, but based on the available scientific information this is questionable for the contamination with microplastics. Antibiotic resistance is another emerging issue which has called for the attention from scientific communities. According to the World Health Organization (WHO), antibiotic resistance has become a critical global public health issue of this century (WHO, 2014). It is thus of great importance for water industry to understand their presence in water and control them with effective measures.

From the point of view on management of micropollutants, the linkage of regulations and management measures between discharges of contaminants, uses of risk assessment tools, establishment of water quality standards, and monitoring requirement is essential for effective water resource management. The workshops held in the 2017 and 2019 IWA Micropol Conferences concluded that only environmentally friendly, non-persistent substances should be used and only responsible doses of pharmaceuticals (for both humans and animals) should be applied as well as requiring more transparency in the handling of chemicals. In addition, it has become clear that an implementation of advanced wastewater treatment processes for the removal of micropollutants without a legal basis only leads to local initiatives. In any case, it is considered central to define treatment goals rather than procedures.

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Biofilms – innovative technologies

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Introduction

Biofilms are complex biological structures that form on almost all moist or submerged surfaces (Flemming et al., 2016). They are highly relevant to natural and engineered water systems and can play both beneficial and detrimental roles. Beneficial biofilms include those harnessed for contaminant removal, such as biological filters for drinking water treatment, moving bed biofilm reactors (MBBRs) for wastewater treatment, and riverbank filtration for groundwater treatment. Detrimental biofilms include biofouling layers on reverse osmosis membranes, biofilms in water distribution pipes, and algal mats in lakes.

Biofilm technology can be divided into three major areas: microbial processes and ecology, reactor technology and design, and modelling. These are discussed below.

Key terminology

- Biofilms – biological structures consisting of microbial cells and an extracellular polymeric matrix.
- EPS – Extracellular polymeric matrix that binds cells to each other and typically to a surface.
- Biofilm reactor – a vessel or compartment with biofilms that degrade contaminants.
- Microbial ecology – the study of microbial communities.

Existing knowledge of Biofilms

Microbial processes

Biofilms consist of bacteria, yeasts, fungi, algae, or other microorganisms embedded in a self-produced matrix of extracellular polymeric substances (EPS) (Flemming and Wingender, 2010). A unique feature of biofilms is the presence of substrate gradients, which leads to a stratification of microbial activity (degradation rates) and microbial communities. The close proximity of different microbial groups within the biofilm allows for complex ecological associations and interactions. Also, it allows for multiple types of processes, for example, aerobic, anoxic, and anaerobic, to occur simultaneously.

An important goal in biofilm applications is obtaining a desired structure and function. The structure typically refers to physical configuration of the biofilm, such as the thickness, porosity, roughness, EPS composition, mechanical properties, and density. It may also refer to the spatial distribution of bacteria. The function often refers to the microbial groups or functional guilds within the biofilm, including their biocatalytic activity.

The biofilm structure can be studied with tools such as confocal laser scanning microscopy (CLSM), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). Optical coherence tomography (OCT) is an emerging tool for studying biofilm morphology non-destructively at the meso scale (Wagner and Horn, 2017). The distribution of macromolecular components (e.g., polysaccharides, proteins, lipids, and nucleic acids) of biofilm cells and its EPS matrix can be assessed using soft X-ray scanning transmission X-ray microscopy (STXM), micro Raman spectroscopy (Zhang et al., 2019), or compound-specific fluorescent stains (Schlafer and Meyer, 2017).

The function of biofilms can be determined using molecular tools, such as quantitative polymerase chain reaction (qPCR). *In situ* molecular tools, such as fluorescence *in situ* hybridisation (FISH), can be combined with microscale chemical sensors to explore the structure and function of biofilms (Schramm, 2003). Droplet digital PCR is an emerging alternative to qPCR (Hindson et al., 2013). Metagenomics tools are increasingly used in biofilm research. Using next generation sequencing (NGS) of 16S rRNA gene amplicons, also referred to as metabarcoding, the entire microbial community, or "microbiome," of biofilms can be studied. DNA amplicons created by PCR are sequenced on an NGS platform, providing detailed community compositions as well as relative abundances (McIlroy et al., 2015; Santillan et al., 2019). With curated public databases like Silva (Quast et al., 2013), 16S rRNA gene sequences can be classified. The activated sludge-specific database MiDAS (http://www.midasfieldguide.org) (McIlroy et al., 2015) can be more useful for wastewater biofilms.

It is important to consider that (i) bacteria can usually only be identified from phylum to genus level, meaning that pathogenic species often are not detectable; and (ii) reported abundances of taxa are always relative, therefore they do not represent absolute concentrations. Note that the latest version of MiDAS has some full-length 16S rRNA gene sequences, allowing species level discrimination.

Increasingly, researchers are employing “shotgun sequencing” to comprehensively sample all genes in all organisms in a given complex sample, i.e., the metacommunity. This provides more complete view of the functional gene structure of the microbial community (Santillan et al., 2019). It also provides greater taxonomy resolution, functional profiling, and cross-domain (Bacteria, Archaea and Eukarya) coverage than 16S rRNA gene amplicon sequencing, without the PCR-associated biases. However, this approach is more expensive, produces large amounts of data, and required more bioinformatics analyses, such as reads assembly and binning, metabolic function profiling, and antibiotic resistance gene profiling. Available databases in for microbial ecosystems are limited. However, novel organisms and metabolic pathways are being identified through metagenome-assembled genomes (MAGs), a single-taxon assembly based on one or more binned metagenomes that may represent an actual individual genome.

Research on biofilm reactors has revealed novel new metabolic pathways. An anaerobic ammonium oxidation (anammox) process was discovered in a pilot-scale denitrifying fluidised bed biofilm reactor. From this system, a highly enriched microbial community was obtained, dominated by a single deep-branching planctomycete, *Candidatus* Brocadia anammoxidans (Jetten et al., 2001). Since that time, the utilisation of anammox microorganisms in biofilm reactors has proved popular, cost effective, and efficient (Liu et al., 2020).

The investigation of freshwater sediments has brought to light a microbial consortium that couples anaerobic methane oxidation to denitrification (Raghoebarsing et al., 2006). This process, also known as DAMO, is performed by bacteria of the NC10 phylum and archaea belonging to the ANME-2D lineage, which respectively reduce nitrite and nitrate (Ettwig et al., 2010; Haroon et al., 2013). Owing to their ability to remove nitrogen by utilising methane as a sole carbon source, intensive research on ways to integrate DAMO microorganisms in bioreactors for nitrogen and methane removal is ongoing. Biofilm reactors has proven particularly useful, as they can facilitate the retention of the slow-growing DAMO microorganisms (Xie et al., 2017). Studying further the physiology of DAMO microorganisms and the interplay between them and other microorganisms is, however, needed to ensure their successful application in engineered environments (Guerrero-Cruz et al., 2019).

The continued development of knowledge about phototrophic biofilms has elucidated their utility for nutrient removal from wastewater, heavy metal accumulation and water detoxification, oil degradation, agriculture, aquaculture, and sulfide removal from contaminated waste streams (Kesaano and Sims, 2014; Wang et al., 2017).

Wastewater treatment processes can be a significant source of nitrous oxide (N_2O), a powerful greenhouse gas (GHG). While the microbial basis of N_2O emissions from nitrifying and denitrifying bacteria are fairly well understood, the mechanisms of N_2O emissions from biofilm systems can be quite different due to substrate gradients and microbial stratification (Sabba et al., 2015; Sabba et al., 2018). Further research is needed to better manage N_2O emissions from biofilm processes.

Biofilms are often correlated with opportunistic pathogens in premise plumbing systems (Liu et al., 2016; Wingender and Flemming, 2011). In particular, there is increasing concern about *Legionella* spp. in drinking water systems (Shen et al., 2015). Biofilm formation is thought to be related to water residence time in premise plumbing systems, which may be increasing due to greater use of water-conserving fixtures, lower building occupancy, and, more recently, building shutdowns or low occupancy due to the Coronavirus pandemic (Ley et al., 2020).

The EPS matrix of biofilms are thought to consist primarily of polysaccharides, proteins, and nucleic acids (Karygianni et al., 2020) although recent research suggest that lipids and glycosylated proteins are more important than proteins and polysaccharides (Lin et al., 2018). The EPS provides biofilms with mechanical stability, mediates bacterial adhesion to surfaces, and serves as the three-dimensional polymer network that interconnects and transiently immobilises bacterial cells inside a biofilm (Flemming and Wingender, 2010). EPS helps entrap particulate matter from the bulk liquid, convert non-readily biodegradable substrate into readily biodegradable substrates, agglomerate metals such as selenium (Gonzalez-Gil et al., 2016), and promote the formation of granular sludge.

While the constituents of the EPS matrix are generally known, their full characterisation and function remain elusive (Seviour et al., 2019). The kinetics of EPS production, the rate they degrade, their contribution to metabolic kinetics and biochemical transformation rates owing to a biofilm are poorly understood. Thus, biofilm models explicitly describing EPS are few.

An emerging area of research is on the mechanical properties of biofilms, that can impact biofilm deformation and detachment. Several review papers have been published in recent years (Gordon et al., 2017), and new models are being developed to incorporate mechanical properties and include deformation (Li et al., 2020; Tierra et al., 2015).

Many micropollutants, including pharmaceuticals, have been shown to be degrade biologically. In some cases, biofilm processes can out-perform the suspended growth process. This may be due to the greater diversity of microbes and redox conditions in biofilm processes (Torresi et al., 2016). The biochemistry and microbiology of micropollutant transformation – in context of biofilms – is under active investigation, and the identification of the responsible organisms, the role of different functional guilds, the contribution of co- versus primary metabolisms, and the significant of biofilm redox conditions are all under examination.

Reactors

Biofilm reactors are the primary means to harness biofilms to treat water. Biofilms transform environmental pollutants, such as carbon (C), nitrogen (N), and phosphorus (P). Several types of biofilm reactor have been utilised for water treatment, but currently the main focus is on biological aerated filters (BAFs), moving bed biofilm reactors (MBBRs) and integrated fixed-film active sludge (IFAS) processes, membrane-aerated biofilm reactors (MABRs), and granular sludge processes.

BAF, MBBRs and IFAS processes are mature technologies that continue to evolve. Hybrids BAF/MBBR like the BIOSTYR DUO and the CFIC are probably the most compact treatment for C and N removal in municipal wastewater treatment. State-of-the-art MBBRs and IFAS processes use submerged free-moving biofilm carriers, and can be used for C oxidation, nitrification, denitrification, and deammonification (McQuarrie and Boltz, 2011). A new area of application for MBBRs with increasing interest is its utilisation for anaerobic treatment of industrial and municipal wastewater. New developments in MBBR carrier design allows for the control of biofilm thickness, avoiding clogging and thus eliminating problems with past media shapes/types (Arabgol et al., 2020).

The MBBR is an effective platform for simultaneous partial nitritation and deammonification. The ANITA™Mox process is a commercially available system to treat sidestream Nitrogen-rich effluent using the MBBR or IFAS configuration (Veuillet et al., 2014). An increasing number of full-scale ANITA™Mox systems exist in Europe and the USA.

Granular biomass has long been used for anaerobic wastewater treatment in upflow reactors. This has been mainly limited to industrial wastewater systems. More recently, an aerobic sequencing batch reactor (SBR) based technology has proved an effective and highly promising environmental biotechnology for municipal wastewater treatment. Aerobic granules can be formed and maintained in SBRs (Beun et al., 2002). Application of an anaerobic feeding stage is crucial to obtain a stable and scalable aerobic granular sludge technology (de Kreuk et al., 2005). In the past eight years, around 100 aerobic granular sludge processes have been operating or are under construction on all continents except Antarctica. All of these WWTPs plants are designed for biological nutrient removal from municipal wastewaters.

The NEREDA™ process is a commercially available aerobic granular sludge system that has been used for successful biological nutrient removal in screened/degritted wastewater or primary effluent. The first full-scale NEREDA™ process is located at the Garmerwolde WWTP, Netherlands (Pronk et al., 2015). The largest facility is in Ringsend (Ireland) with a capacity of 600 MLD or 2.4 million PE. This technology only occupies 25–33 % of the footprint of a traditional nutrient removal process, and saves significant energy due to the absence of most of the mechanical equipment needed in a conventional process. The NEREDA™ process maintains a constant liquid/biomass volume. The filling, settling, and decanting steps occur simultaneously during approximately 25–33% of the operational period. The remainder of operation is reserved for aeration (i.e. reaction period). Approximately 10–15 minutes is required to achieve reactor quiescence. These typical operational parameters, along with conducive influent wastewater characteristics, result in effluent waters having TN < 5 mg/L and TP < 1 mg/L.

Another application of granular sludge reactors is for the implementation of anaerobic ammonium oxidation (anammox) based processes for especially the treatment of anaerobic digester effluents. Simultaneous partial nitritation and anammox of high ammonia-nitrogen concentration waste streams has been implemented in MBBR as well as granular sludge processes. For the latter upflow sludge blanket reactors as well as reactors where cyclones or sieves are used to selective retain the granular anammox biomass in the reactor are used (Lackner et al., 2014). Current research and development focus on the use of cyclones or sieves for retaining granular biomass in the mainstream of continuous flow municipal wastewater treatment processes.

The use of mobile biofilms and aerobic granules in continuously flowing wastewater treatment processes is emerging as viable and cost-effective ways of treating municipal and industrial wastewaters. The Mobile-Organic Biofilm, or MOB, (Nuvoda, USA) process includes mobile-biofilms and their retention screens with a bioreactor and liquid and solids separation process. Biofilm retention screens may be integrated with bioreactor effluent or waste-solids streams to retain the mobile biofilms. Lignocellulosic materials, e.g., kenaf, have been utilised as mobile-biofilm carriers. They are processed to provide a consistent and repeatable surface area for biofilm growth, but the specific surface area that they provide depends on biofilm thickness (Boltz and Daigger, 2022). It can be operated as a biofilm reactor or hybrid biofilm and suspended biomass process. The inDENSE (World Water Works, USA) process utilises hydrocyclones includes aerobic granules and utilises hydrocyclones to accumulate them in a wastewater treatment process. The inDENSE process relies on favourable wastewater characteristics and environmental conditions that promote the formation of aerobic granules. An interesting development is the recovery and use of the EPS matrix of the wasted granular sludge as a gel-forming biopolymer. Such polymers cannot be derived from oil-based chemistry, only from biological resources. This makes the product a potential economic attractive resource that can be produced from wastewater. The current state of the technology is a demonstration facility in the Netherlands operated by the Dutch water boards. It can produce 500 tons of polymer per year, and the polymer is marketed under the tradename Kaumera.

A biofilm reactor that is emerging rapidly is the membrane biofilm reactor (MBfR) or MABR when used to supply O_2. In these systems, a gaseous substrate is delivered directly to the base of the biofilm via diffusion through a gas-permeable membrane (tubular, hollow-fibre, or flat) on which a biofilm grows. The gaseous substrate can be the electron donor or electron acceptor. Typically, the electron donor and electron acceptor are subject to counter-diffusion, as one diffuses from the bulk liquid and the other from the membrane lumen (Nerenberg, 2016; Rittmann, 2018). The most common electron donor is hydrogen gas (H_2), creating the H_2-based MBfR (Rittmann 2018), although methane gas (CH_4) also has been studied (Lv et al., 2018). H_2-based MBfRs have been demonstrated for the biological reductions and removals of nitrate, nitrite, perchlorate, bromate, selenate/selenite, arsenate, and chromate (Zhou et al., 2019). The common electron acceptor is oxygen gas (O_2), and the O_2- or air-based MBfR is commonly known as the membrane-aerated biofilm reactor (MABR) (Martin and Nerenberg, 2012; Syron and Casey, 2008). As the MBfR allows for precise control of the delivery capacity of the gaseous donor or acceptor, biofilms with defined redox conditions can be developed for simultaneous oxic/anoxic process. For example, the MABR is used for nitritation/anammox and biodegradation of aromatics by a combination of aerobic monooxygenation and anoxic respiration (Pellicer-Nacher et al., 2010). The H_2-based MBfR is available from APTwater (Pittsburg, California) for removals of nitrate and perchlorate. The MABR may be procured in North America as Suez's ZeeLung™ process or Dupont's OxyMem™ process. These O_2-based processes are well suited for combined carbon oxidation and nitrification, nitrification, denitrification, partial nitritation and deammonification.

The continuous enhancement and implementation of new water-quality regulations and the discovery of new processes has made mature biofilm reactor types relevant to current trends and challenges that face this community. For example, the US Environmental Protection Agency (EPA) has enacted effluent guidelines for steam-power generation facilities that requires total-dissolved selenium concentrations to be less than 0.029 mg/L. Selenium pollution and related water quality regulations have impacted agriculture, mining, power (coal and oil) industries, and municipal wastewater treatment plants. The use of expensive reagents and the production of hazardous residues makes the use of physicochemical treatment impractical. As a result, the biological transformation of selenate to selenite, and selenite to elemental selenium is more economical, and biofilm reactors capable of operating under anaerobic conditions are employed (Boltz and Rittmann, 2021). The most widely used processes for selenate removal are Suez's ABMet® and Frontier's SeHAWK®, but other platforms are viable. Both are fixed-bed biofilm systems that are promote heterotrophic reductions by the addition of organic donor substrates. H_2 also can be used as an inorganic donor in the MBfR (Zhou et al., 2019)

Biofilms play a special role due to their capacity to generate electrical current in microbial electrochemical cells (Logan et al., 2006; Rittmann, 2018), which are sometimes called bioelectrochemical systems. The foundation for microbial electrochemistry comes from a set of bacteria that have the ability to oxidise simple organic molecule and respire those electrons to the anode of an electrochemical cell. These bacteria have been given different names: anode-respiring bacteria (ARB) and exoelectricigens. The key here is that they carry out extracellular electron transport that sends the electrons to the anode and generates energy for the bacteria (Ritmmann and McCarty, 2020; Rittmann, 2018). Once the electrons reach the anode, they are conducted through an electrical circuit to the cathode, where they are used to generate value either as electrical power by reducing O_2 to H_2O, hydrogen peroxide (H_2O_2) through partial reduction of O_2, H_2 gas by reduction of H_2O, or organic molecules by reduction of inorganic carbon (Rittmann, 2018; Rittmann and McCarty, 2020). Microbial electrochemical cells are still at the research and development stage, although some commercialisation efforts are on-going.

Unwanted biofilms: toward control

The deleterious role of biofilms on membranes is also an area of concern to process designers and biofilm researchers. Membrane biofouling is a costly operational concern that is a feed spacer problem in spiral wound membranes (Vrouwenvelder et al., 2006). Other unwanted biofilms are in drinking water distribution and probably sewers. Another approach to dealing with undesired biofilms that grow on membranes is to tolerate their existence, and focus on increasing hydraulic conductivity of the growing biofilms rather than trying to prevent their formation; ultimately one may benefit from the biological activity in a biofilm to improve permeate quality (Chomiak et al., 2015).

Biofilm modelling

Given the complexity of biofilms, modelling is a useful tool that may be used to understand and systematically evaluate them and predict system response to their incorporation. For example, modelling may be used to optimise a process for performance and cost effectiveness, predict existing system response to a range of simulated operating conditions, and troubleshoot undesirable performance. Biofilm models are commonly used for research, and the design and evaluation of bioreactors (Morgenroth et al., 2000). A consensus description and comparison of biofilm models was presented by Morgenroth et al. (2000). Rittmann et al. (2018) presented a framework for good biofilm reactor modelling in practice. Widespread development and application of one-dimensional biofilm models for engineering practice has occurred (Boltz et al., 2010). Even further simplification to 0-D models, neglecting spatial variations and lumping the reaction-diffusion process into apparent half-saturation coefficients of Monod kinetics, could be considered (Baeten et al., 2018). Nevertheless, multi-dimensional biofilm models (Martin et al., 2013) have enhanced many areas of biofilm research and technology development. To date, however, a dichotomy exists between the fields of usefulness for biofilm models: one-dimensional biofilm models are typically used for engineering practice and biofilm-reactor research and development, while multi-dimensional biofilm models are effective research tools.

Numerical, one-dimensional biofilm models are encoded into a majority of commercially available wastewater treatment plant simulators. Amongst these simulation platforms, methodology of modelling the simultaneous diffusion and reaction of soluble-state variables is similar, but the method of simulating solid state-variable movement and biofilm detachment varies significantly. In addition, model users generally lack flexibility to easily define and modify the function that describes biofilm detachment.

The importance of bulk-liquid hydrodynamics and system idiosyncrasies (e.g., biofilm carrier type and transport) are an integral consideration for biofilm and biofilm reactor modelers. Biofilm models have been used to address topics most relevant to environmental biotechnology including hybrid systems, membrane biofilm reactors, aerobic granular sludge, GHG emissions, phototrophic biofilm, and microbial fuel cells.

In addition to bioreactor advancements, strategies for the eradication of deleterious biofilms have resulted from biofilm use. For example, biofilms persistently foul membrane filters. As biofilms grow on membrane surfaces, they increase hydraulic resistance and either decrease filtration fluxes or increase energy costs for a given flux. Many advances in the current understanding of biofilm-associated membrane fouling have been expounded from modelling applied to reverse osmosis systems.

An important question is how to model fluid flow through biofilms. Several recent studies considered the biofilm as a porous media, with Darcy-type behaviour. However, studies also have shown that the biofilm can be compacted during filtration, indicating a reduction in porosity with higher pressure gradients and flows (Jafari et al., 2018).

Overall, it is clear that there are several biofilm model features which can be described with different degrees of complexity. They concern, for example, biological and physicochemical transformations, liquid-phase transport (hydrodynamics), biomass retention and distribution, intra-biofilm transport (diffusion), liquid-biofilm mass transfer (detachment, external mass transfer limitations), gas phase transport, and liquid-gas mass transfer. In a review of 167 granular sludge models, Baeten et al. (2019) explained chosen modelling approaches based on the different reactor types and goals wherever possible. However, they found that some assumptions appeared to be common within certain fields of research without a clear reason. Clearly defining the modelling goal is paramount to find the appropriate model complexity for a given application, and to differentiate between the many available models.

General trends and challenges

This paper has presented evidence of the relevance and future significance that research, development, and implementation will play in the following areas:

- biofilm ecology, and elucidating the functional and mechanical role of EPS;
- greenhouse-gas emissions;
- micropollutants (e.g., pharmaceuticals, selenium);
- MBBR/IFAS, aerobic granular sludge, and MBfR/MABRs;
- biofilm and biofilm reactor modelling;
- biofilms on active substrata (e.g., MBfR, MABR, MXC;
- omics tools;
- quantitative use of OCT;
- granular sludge;
- mainstream deammonification;
- biofilm in premise plumbing and risk of opportunistic pathogens.

Conclusions and Research Agenda

Fundamental principles describing biofilms exist as a result of focused research, practical application, and modelling. The use of reactors for the treatment of municipal and industrial wastewaters is a common beneficial use of biofilms. Applied research exists that provides a basis for the mechanistic understanding of biofilm systems. The empirical information derived from such applied research has been used to develop design criteria for biofilm reactors and remains the basis for the design of many biofilm-reactor types despite the emergence of mathematical models as reliable tools for research and practice. There is a gap between our current understanding of biofilm fundamentals and reactor-scale empirical information. Further research is needed to bridge the gap.

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| 2.3 |

Design, operation and maintenance of drinking water treatment plants

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Introduction

The Specialist Group (SG) on the Design, Operation and Maintenance of Drinking Water Treatment Plants was created in 1996 to support exchange between experts in theory and practice. The hot topics of the specialist group (SG) comprise a variety of issues and are continuously evolving with the actual challenges of the field.

Over the past 10 years the core issues on which the Specialist Group has focused its concern and area of activity were mainly related to tackle water quality compliance:

- health risk related to emerging parameters (chemical and microbiological) on drinking water treatment plants;
- natural organic matter (NOM) removal;
- disinfection by-products (DBP) formation control;
- advanced treatment processes for new micro-pollutants removal;
- plant retrofit and upgrade, maintenance procedures;
- optimisation of CAPEX and OPEX for water treatment plants;
- operational feedback from case studies.

Changing imperatives: SDG 6 and inclusivity

The UN Sustainable Development Goal (SDG) 6 aims to ensure availability and sustainable management of water and sanitation for all. Target 6.1 of the SDG 6 aims to achieve universal and equitable access to safe and affordable drinking water for all by 2030.

The mantra ‘leaving no one behind’ which was favourably considered from the point of people that lack access to clean water, is now changing and much attention has also been given to inclusive decisionmaking in drinking water utilities. The call for the inclusion of women and young water professionals in the production and distribution chain of drinking water has been highly acknowledged as a way to accelerate efforts in reaching the SDG 6 targets in time.

The less developed countries of Africa, Asia, and Latin America now account for 80% of the world population. Developing regions will see 97% of the world’s population growth of 1.2 billion people take place between 2013 and 2030, by when 60% of the world’s population will be living in urban areas. In addition, intermittent and prolonged world conflicts, forced migration, and climate change phenomena, are resulting in an increasing number of people, either internally displaced or driven to live in mammoth refugee camps. According to some estimates, as of 2018, about 136 million people were in need of humanitarian assistance including drinking water supply. Thus, ‘leaving no one behind’ warrants adopting an inclusive approach in whatever we do.

Importance of design, operation and maintenance

Operation and maintenance (O&M) of drinking water treatment plants (WTPs) is a crucial element of sustainability, and a frequent cause of failure of water supply service facilities the world over. One of the formidable challenges in realising Target 6.1 is ensuring that the water supplied is safe. In 2012 it was estimated that at least 1.8 billion people were exposed to improved drinking water sources contaminated with faecal matter. It is necessary to note in this context, that the determinants of safe piped drinking water quality are many, and the design, operation and maintenance (O&M) of Water Treatment Plants (WTPs) is just one of them (Table 2.1).

In a desk review of the functionality of wastewater treatment plants in low- and middle-income countries (Water Aid, 2019), Water Aid reported that the challenges to functionality ranged from technical and capacity issues (technology choice, inadequate process design and detailed design, operation not matching design criteria, breakdown of equipment and inadequate technical back up, etc.), financial considerations (inadequate analysis or consideration of operational

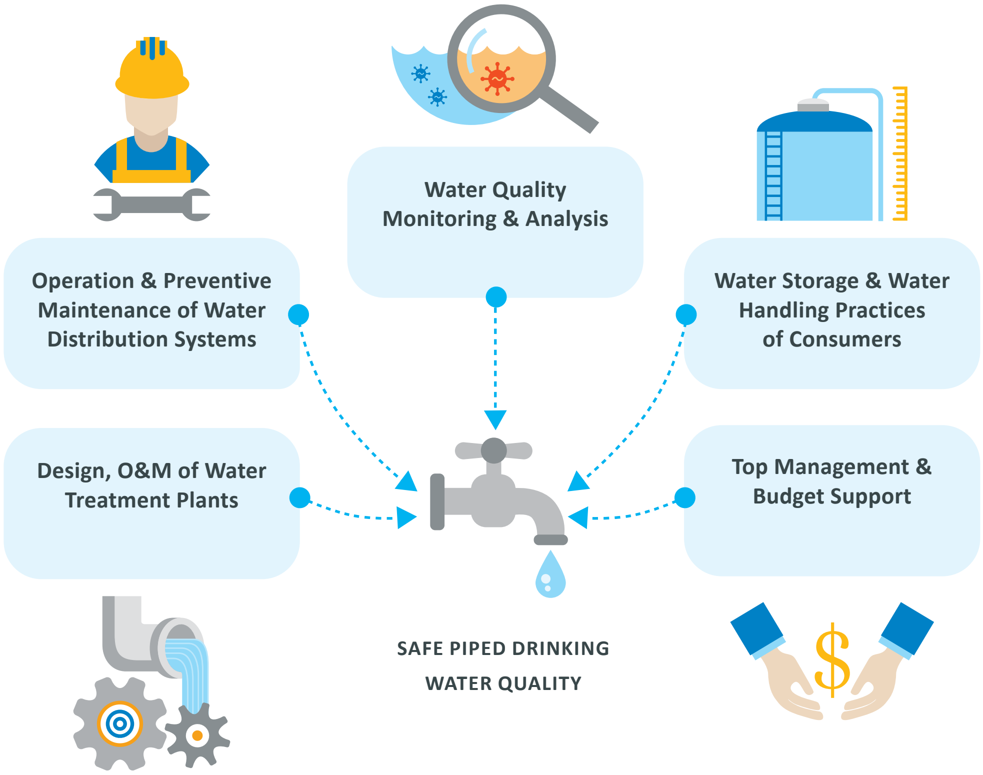

Figure 2.1: Determinants of Safe Piped Drinking Water Quality

expenditure), and institutional blockages (weak management, failure of procurement systems). These challenges are very much applicable to the design, operation and maintenance of drinking water treatment plants as well.

In the design of WTPs, it is no doubt possible to avoid some of the likely O&M problems, through proper planning and intelligent design, as in the case of, for example, Slow Sand Filtration plants (Raman and Haraprasad, 1980). When it comes to O&M, however, no matter how well a WTP may have been planned, designed and constructed, it will still fail if it is not operated and maintained properly. The contributing factors for such a failure are many, and often transcend the scientific/technical domain as stated earlier.

The most common operational deficiencies and their consequences in the O&M of some of the WTPs in a typical developing country situation are cited with reference to, e.g. treating ammonia-laden raw water (Haraprasad, 2008) (Table 2.1).

While the operational deficiencies noted are only the symptoms, the underlying causes lie elsewhere, often in the managerial, financial and capacity building domains, and are very common in many developing countries.

Irrespective of the variations in engineering and process designs for drinking water treatment, some of the typical underlying causes for operational deficiencies noted are as follows:

- Lack of proper functional segregation and clear-cut accountabilities between the Process Control Laboratory and the compliance monitoring function.
- Ill-conceived reporting structures and supervisory practices for process control and compliance monitoring within the water utility, with no clear-cut accountability to rectify a water quality situation.
- Lack of highest support and importance to water quality compliance monitoring in terms of personnel, procurement, coordination and operational support needed for the task.
- Lack of capacity in terms of personnel, expertise, equipment, chemicals, spares, etc. notwithstanding the existence of standard operating procedures and manuals of operation and maintenance, and troubleshooting in emergencies.
- Budgetary constraints, lack of top management support, etc.

All the above causes and many others on the ground (both technical and non-technical) do affect sustainable production and supply of safe drinking water to consumers.

In the case of rural areas where 40% of the world population is expected to live by 2030, the design, operation and maintenance of community (rural) water supplies present their own specific challenges, in terms of design (single, or multi-village schemes, simple, sustainable process and engineering), amenable to community operation, cost-effective maintenance, capacity building needs, etc.

In a humanitarian context, water is probably the most urgent need of individuals, who will use any available source, polluted or not, with the consequent hazard of epidemics, if provision is not made quickly for safe water. Sometimes the amount of water available may govern the number of evacuees/refugees who may be received and handled in a particular site. The

Table 2.1 Common Operational Deficiencies in a few WTPs of a developing country

SL. NO.	OPERATIONAL DEFICIENCIES	CONSEQUENCES / IMPLICATIONS
1	Lack of proper flow measuring equipment	• Hydraulic overloading of treatment units (e.g. mixing channels, sedimentation tanks, filters) / affects treatment process • Improper blending of groundwater & surface water for dilution and reduction of nitrates or for reduction of ammonia concentration & downstream treatment
2	Inadequate aeration in bio-filters	• Inadequate ammonia removal → high chlorine demand → low free residual chlorine (FRC) levels in WTP
3	Ill-maintained/non-functioning chemical dosing systems	• Improper dosing of chemicals → affects unit processes
4	Single point addition of chemicals	• Improper mixing & process inefficiency • In large clear water tanks, it leads to short-circuiting of water flow →inadequate contact time → low FRC in outgoing water
5	Practically no process monitoring or control	• Affects ammonia removal • Affects turbidity removal • Affects disinfection efficiency
6	Lack of water for filter backwashing/infrequent filter washing	• Affects filtered water quality
7	Chemical addition as per availability and not as per process requirement	• Affects turbidity removal • Affects disinfection efficiency
8	Lack of chemical stocks and spare parts	• Affects unit processes and operations

defining conditions of design, emergency operation and maintenance of water supply facilities/services in such cases and in prolonged emergencies, will be different from those applicable for conventional water treatment plants located in a development context.

It would therefore be the endeavour of the SG to address the major constraints which prevent the achievement of sustainability, by addressing in the group's agenda and operational plans, a wide range of factors (technical, managerial, capacity building, financial, and inter-Group linkages) that affect the design, operation and maintenance of drinking WTPs both in humanitarian and development contexts.

Each water utility or situation will have its own opportunities and challenges in tackling these issues, there being no 'one-size-fits-all' remedy, and the SG does not intend to come up with site-specific solutions.

Specialist Group priorities

- A wide range of issues relating to the drinking water treatment plants, including: health risk related to emerging parameters (chemical and microbiological), NOM removal, advanced treatment processes for new micro-pollutants removal, application and case studies and solving operational issues as well as using smart tools for analysing plant data.
- Design and O&M issues of drinking WTPs in developing countries, climate change and humanitarian emergencies.
- Anticipate the water quality regulations evolution and continue the implementation of Water Safety Plans for adapting the Water Treatment Plants existing infrastructure and operational practices to ensure compliance with the future requirements.
- Enhance networking and exchange of practices and experience on operational and managerial issues for those involved in the design and operation of drinking water

treatment plants and contribute to better understand the operational needs (ex. in terms of Training) and help solving operational problems.

- Act as repository and clearing house of information, knowledge and best practices in design, operation and maintenance of drinking water treatment plants the world over.

General trends and new challenges

Today the key enabling technology that will bring transformation in this field is definitely the trend to digitalisation and the smart plant approach. It offers new opportunities for optimisation of the plant operation and enhance plant management (chemicals dosing, workforce management, energy optimisation). Further, big data and the numerical technological revolution (connected objects, Internet of things, sensors and IT smart platforms) will impact and transform the way we will operate our plants in the future. For example, the advancement in sensors and monitoring tools can normalise the quality of drinking water across countries and provide data for informed decision making. But as digitalisation has proved to be a game changer in ensuring increased efficiency of drinking water treatment plants, issues of cybersecurity need immediate attention and planning.

Therefore we have observed the need to include some other important issues to our water future such as the following:

- plant asset management;
- smart operation tools development and implementation of best practices;
- development of standards for digitalisation in the water treatment plants;
- power consumption and energy management;
- life cycle analysis;
- securing produced and distributed water by on-line measurement of quality and control with micro-sensors (including direct potable reuse).

In terms of the water treatment solutions for the less developed areas, point-of-use (POU) systems are the key solutions for a user-friendly, low-cost, and low-maintenance water treatment. The feasible POU technologies include flocculation and coagulation, filtration (include biosand filtration and membrane filtration), and disinfection, which all have shown high efficacy in removing pathogens and turbidy from raw water sources. Future research areas for POU technological advancement include the following:

- For flocculation and coagulation, biodegradable coagulant development and coagulant dosage optimisation, etc.

- For biosand filtration, raw materials exploration for biosand construction, sorption kinetics analysis, etc.

- For membrane filtration, cost-effective ceramic membrane material development for long-term stable membrane performance, gravity-driven membrane filtration process analysis and optimisation, etc.

- For disinfection, solar disinfection development and nanoparticle disinfection technology assessment, etc.

Recommendations on future hot topics and research development agenda

One of the key topics in respect to water treatment plant operations reliability is the water safety plans (WSPs) and ISO22000 certification. These have been successfully applied in different countries and have provided benefits. Their implementation should continue to be promoted among the operators of drinking water treatment plants. These benefits include an improved confidence of clients and health agencies, a better control of hazards, and a better control of operations. For WSP to be effective and accepted, specific performance metrics or indicators have been defined and standard methodologies have been developed to successfully implement them. There is a need to share a common approach for implementation of WSP and exchange on the relevance of the selected operational indicators and metrics in different countries and sites.

Another important issue is associated with climate change including an increase in extreme events (drought, rains, flooding) resulting in water resources quality degradation (increased microbial and chemical pollution, eutrophication, etc.) – both of which present challenges for water suppliers. These extreme events will have an impact on WSP evolution since the WSP-led improvements can strengthen system resilience, leading to sustained confidence in the production of drinking water during these changing times. The challenge is the merging of the WSPs and the watershed management programs (WMSPs) implicit for an extreme event but also in order to assess the long term impact of climate change on plant operation issues. For example, the climate change has a significant impact on the increase of NOM level in the water resources. This affects directly the higher cost of chemicals and advanced water treatment processes in order to comply with the public health authorities pressure to reduce DBPs and chlorine level. Therefore NOM in drinking water will grow in importance during the coming years the main areas of research being the following:

- new ways for NOM characterisation, measurement and on-line monitoring;

- innovative ways of NOM advanced treatment and reduction;

- impact of residual NOM for DBPs formation and water bio stability control (biofilm regrowth);
- understanding the mechanisms of how NOM contribute to the mobilisation and transport of synthetic materials: reactivity, analysis, treatment and importance of the spread of persistent organic pollutants.

Last but not least, hot topic concerns the implementation of the latest advances in on-line water quality monitoring. The development of new generation of sensors such as the multi-parameter probes on one side and the increasing operators needs on the other side have created opportunities for demonstrating the potential benefits of these innovations.

Different suppliers have developed products in response to the market requirements the main challenges and expectations being the following:

- improvement of Quality of service by ensuring traceability of the relevant water quality indicators;
- enabling of detection of events resulting in a change in water quality and impacting both the health of the consumers and the distribution pipes;
- reduction of non-compliance risks and optimisation of treatment processes;
- enhancing security for sensitive areas and buildings in cities.

Plant operators need to better share information on the benefits from these innovative tools by exchanging operational experience and lessons learned from practical application of the technology in field case studies and to assess the prospects for future development for this technology.

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Biographies:

Dr. Haraprasad Vaddiparthi (former president of the Specialist Group) – WASH and Environmental professional having over four decades of projects design, R&D, consulting, and advisory experience with governments, NGOs, and private sector, in 13 countries of Asia, Africa, and Middle-East. Served with the United Nations Missions and Agencies in different capacities at the WASH Sector policy, strategy, program, monitoring, investment planning, and sector coordination level.

Dr. Jun Ma (current president of the Specialist Group) – Professor at Harbin Institute of Technology and the Deputy Director of the National Engineering Research Center of Urban Water Resources, China. His interest has been in the area of water and wastewater treatment. He has been working in the processes of the advanced oxidation process, coagulation, dissolved air flotation, carbon related adsorbents and adsorption processes, nanoparticles and membranes, heavy metal removal, disinfection and by-products control. He was selected as the Academician of Chinese Academy of Engineering in 2019.

| 2.4 |

Diffuse pollution and eutrophication in a changing world

Authors: *Markus Venohr, Angela Gorgoglione, Luis Bravo Inclán, Eakalak Khan, Leehyung Kim, Ralf Kunkel, Zorica Todorovic on behalf of the Diffuse Pollution and Eutrophication Specialist Group.*

Introduction

Diffuse pollution of surface waters often exceeds the amount of point source pollution, but is much more difficult to assess, localise, quantify and manage than latter. Diffuse pollution occurs on all land-use types and can enter groundwater and surface waters via various pathways. Recent developments all over the world seem to alter or foster diffuse pollution: rapid land-use changes, increasing number and intensities of storm events, and uses of new substances in industry, agriculture and daily products. In developing countries, rapid population growth and urbanisation cause major land-use changes and intensify agricultural activities (Chotpantarat and Boonkaewwan, 2018). This is usually accompanied by increases in applications of pesticides and fertilisers, and emissions through runoff from agricultural and impervious areas (Gorgoglione et al., 2020; D' Amour et al., 2017).

More frequent and severe droughts and floods, heatwaves and storms are some of the effects of climate change and have direct and indirect impacts on diffuse pollution management. Experimental and modelling studies have been recently conducted to evaluate responses of stormwater management practices to climate change (Wang et al., 2017, 2019). As manifold as the involved processes are, so are the transported constituents. Recently, emerging substances like pharmaceuticals, cleaning chemicals, and microplastics are increasingly detected in runoff. However, knowledge on their effects and interactions in aquatic ecosystems remains limited.

Previous research on water quality has mostly focused on a single stressor (one substance or only flow alteration, altered morphology) or treated multiple stressors separately. Multiple stressors can exert synergistic and antagonistic effects which must be considered for surface water quality management actions in order to achieve the goals of the EU water framework directive (Carvalho et al., 2019; Birk et al., 2020). Using process-based and empirical models to predict impacts by multiple stressors (climate, land use and management changes), Mack et al. (2019) reported that the future water quality is dictated by both climate and land use changes and implementing targeted measures is critical to curtail anthropogenic impacts.

This chapter highlights selected recent developments on diffuse pollution and eutrophication. Emerging substances and issues, land-use changes in developing countries, microplastics, low impact treatment, a case study on nutrient pollution management in Germany, and woody buffers are the topics covered.

Emerging topics

Per- and polyfluoroalkyl substances (PFASs), which are a group of emerging contaminants, were detected in urban runoff in Saskatoon, Canada (Codling et al., 2020) and around the San Francisco Bay, California (Houtz and Sedlak, 2012), and runoff from a firefighter training area in France (Dauchy et al., 2019). Perfluorooctane sulfonate, perfluorooctanoate, and perfluorohexanoic acid are the most commonly detected PFASs for the runoff samples collected around San Francisco Bay (Houtz and Sedlak, 2012). Urban and agricultural runoffs continue to be significant sources of pharmaceutical compounds in natural waters. For example, Tran et al. (2019a) detected several antibiotics including erythromycin, azithromycin, and sulfamethazine in a freshwater lake in Hanoi, Vietnam, that received only urban runoff. The presence of antibiotics in natural waters could lead to the generation of antibiotic resistant genes and bacteria.

Contaminant source tracking has emerged as an important tool for the field of diffusion pollution (e.g., Tran et al., 2019b). Knowing the contaminant sources is useful in identifying an effective strategy for preventing and mitigating diffuse pollution. Yin et al. (2020) used markers, such as acesulfame and theanine, to trace contaminant sources and were able to identify misconnected wastewater entries into storm drains as a potential source.

Recently research and practices in several fields have turned towards resource recovery. As an example, rainwater harvesting for agricultural irrigation has been practiced and/or researched in many countries such as India, China, South Africa, and the Netherlands (Velasco-Muñoz et al., 2019). Several research gaps such as factors governing adoption by farmers, economic and financial feasibility, and effect on climate change have been identified to promote the practice (Velasco-Muñoz et al., 2019). Rainwater harvesting can be done in both centralised and decentralised manners but is not always economical.

Rainwater harvesting may also bear some problems. For example, arsenic leached from corrugated iron roofs which fed rainwater harvesting tanks was observed in rural communities in Oruro, Bolivia (Quaghebeur et al., 2019). Spahr et al. (2020) critically reviewed the occurrence and toxicological relevance of hydrophilic trace organic contaminants in urban stormwater. The authors concluded that conventional stormwater management practices such as detention basins, constructed wetlands, and biofilters are not reliable for the removal of these contaminants. They suggested that augmenting activated carbon or biochar to these BMPs could make safe reuse of urban stormwater possible particularly for non-potable applications or groundwater recharge.

Sources and fates of microplastics

Global plastic production has increased rapidly since the 1950s. Although other types of trash are found in the oceans, 60–80% is estimated to be petroleum-based plastic. Microplastics (MPs) is commonly defined as plastics of less than 5 mm diameter and typically origin from two different categories of sources: (a) primary, encompassing MPs that are manufactured in microscopic size, for example in hygiene and personal care products, and (b) secondary MPs originating from larger plastic pieces, broken down by photo-degradation or mechanical abrasion (Siegfried et al., 2017).

MPs originate from point and diffuse sources, yet it is challenging to understand and link sources with emission pathways, transport processes and sinks (Siegfried et al., 2017) as well as the various effects caused to environment and aquatic biota. Although considered biochemically inert, such materials can adsorb other chemical substances, such as persistent organic pollutants (POPs), hence potentially leading to bioaccumulation phenomena (Da Costa et al., 2018).

Main terrestrial sources for plastic pollution are washed street litter, rubbish dumping, manufacturing sites, or surface runoff from agricultural soils as stated by Kumar et al. (2020). Some of the emitted MPs end up in the oceans (Kole et al., 2017), via rivers or the atmosphere (Wetherbee et al., 2019). Marine plastics also result from coastal tourism, fishing, among others (GESAMP, 2015). The size of emitted MPs depends on the source. Car tires through wear and tear emit microplastics 2–50 times larger than airplane tires, artificial turf, brake wear and road markings. Primary MPs sources are likely to be transported through drainage systems and into wastewater treatment influents. Despite some sewage treatment are able to remove up to 99.9% MPs particles from wastewater, the total amount of particles entering the system may still allow a significant number of plastic particles to bypass filtration systems and be released into the environment with effluent (Horton et al., 2017).

The available literature suggests that primary and secondary MPs are likely to be found ubiquitously across terrestrial and freshwater environmental compartments (Horton et al., 2017). There are still multiple research gaps that should be adequately addressed, in order to obtain a realistic assessment of MPs prevalence in the environment (Da Costa et al., 2018) a common issue is the substantial level of confidence in what is unknown (GESAMP, 2015).

There is an urgent need to improve our understanding on the characteristics of point and diffuse MP sources, diffuse sources occur over a wide area and are much more difficult to characterise. Other key knowledge gaps include the volume and composition of MPs released to the environment, their behavior and fate under varying environmental conditions and how MP characteristics influence their toxicity. Further, interactions between MPs and biota need to be further studied and understood.

Current developments of land-use and water quality changes in developing countries

Water-quality protection and restoration are great challenges that the population of developing countries is facing as shown by several studies all over the world emphasising the importance of water for the sustainable development of societies (Giri and Qiu, 2016). Various examples from Asia, Latin America, and Africa prove massive land-use changes and associated impacts on water quality and drinking water production.

Severe land clearing for agriculture and urbanisation has shown negative impacts on the fragile Asian highland ecosystems. During the past decade a massive transformation of forested to agricultural land was observed in Malaysia (Razali et al., 2018) and similarly in Thailand, were agricultural land (paddy fields, field crops, and perennial crops) and urban areas increased (Chotpantarat and Boonkaewwan, 2018). In Uruguay, in the Santa Lucía watershed, since 2013, drinking water supply for most of the country’s population has been impacted by cyanobacterial blooms inducing bad odor and taste. This was associated with increased agricultural and livestock farming, dominating this catchment, and increasing total phosphorus concentrations in surface waters (Gorgoglione et al., 2020).

This anthropisation process directly influence water quality, most prone to contamination by effluents neighboring urban and agricultural areas (Calijuri et al., 2015) and usually characterised by a general increase in concentrations of nutrients in surface waters (Namugize et al., 2018). In Ethiopia, in the Gilgel Gibe catchment, agriculture was found to have the highest pollution loads and thus the most significant effect on water quality, followed by urban settlement (Woldeab et al., 2019). Such land-use changes have been shown to, directly and indirectly, deteriorate the quality of receiving surface water, in particular if done in an unplanned and unsustainable manner (Razali et al., 2018).

In developing countries, rapid water-quality degradation was found for many watersheds undergoing a massive land-use transformation during the past decades. Recent studies helped to identify sources and emission pathways of pollutants and the associate land-use activities, providing fundamental knowledge for watershed managers. However, for these fast-developing watersheds, flexible management strategies have to be derived and put into action to prevent a further deterioration of water quality and to ensure a sustainable use of land and water resources.

Under climate change, current developments in water availability and quality may further exacerbate. Coming research studies therefore need to address options for an adapted and affordable agriculture and urban development.

Low impact urban stormwater treatment with nature-based solutions

Urban stormwater from impermeable surfaces often contains considerable amounts of particulates, organics, nutrients, and heavy metals generated from various anthropogenic activities. Stormwater management to avoid uncontrolled emissions therefore, as a vital component of urban planning, often involve quantitative and qualitative considerations to solve flooding and water quality problems simultaneously. The application of nature-based solutions (NBS), such as the application of low impact development (LID) techniques and development of green infrastructures (GI), can efficiently reduce peak runoff volumes in urban areas to prevent flooding incidents. Beyond this, NBS support societal challenges by securing human well-being and biodiversity benefits (IUCN, 2016), and as such provide a comprehensive approach in improving urban ecology (Guo et al., 2020).

Sustainable urban drainage systems are used in the European Region to minimise flood risks and to incorporate nature-based processes into grey infrastructures (Davis & Naumann, 2017). Some Asian countries adopted NBS for management and policies, like the Water Environment Conservation Act and Environmental Impact Assessment Act (Shafique & Kim, 2018) in South Korea. This trend of managing stormwater sustainably through NBS and GI cannot be seen in isolation as involved green infrastructures also provide vehicle for economic growth, driving social change and providing health benefits that are of interest to multiple stakeholders. Governments' policies across the globe including local policies are recognising vital services of NBS through their contribution to sustainable development by creating vibrant sense of place thereby attracting residents and businesses and at the same time supporting the grow of local economies.

These green projects, providing multiple benefits to different stakeholders, need a shift in the ways they are identified and funded. Urban planners need to assist in driving these opportunities through major infrastructure developments and planned regeneration schemes. There are emerging trends that bring together stakeholders and local communities to create and maintain NBS structures and show ways to fund such projects by multiple stakeholders investments, including crowdfunding.

Practitioners are embracing new digital tools to enable rapid mapping of NBS opportunities including high resolution load allocation models for water quality or upland Natural Flood Management (NFM). This mapping, coupled with monetisation of economic, environmental and social benefits, provides an evidence-based approach allowing strategic planning and site-specific implementations (Todorovic, 2016). When combined with an understanding of stakeholders needs and potential benefits this can provide a compelling adjustment to the development of business cases for investment in NBS and bring partnerships in delivery.

There is urgent need to better assess water quality improvements using NBS structures and any difference in their performance in different climates and under different maintenance regimes. In addition, research into how to design these structures to optimise water quantity and water quality performance is required.

Managing nutrient pollution in Europe – a case study of Germany

Mineral and organic fertilisers applied for agricultural uses are still regarded as the most relevant source of nitrate polluting groundwater and the marginal seas worldwide (Billen et al., 2013). In Germany it is, further, the main reason to fail drinking water standards for decades (e.g. Rosenstock et al., 2015). Accordingly, in Europe, various water legislation, such as the EU Nitrates Directive, the EU Water Framework Directive, and the EU Marine Strategy Framework Directive, oblige the implementation of measures to reduce fertiliser applications and impacts on groundwater and surface waters.

In many countries the linkage between legislation and the requirements by water management is vague or goals are misaligned. In addition, thresholds or goals between among legislations are not always compatible. In Germany, for instance, detailed regulations on fertilisation levels and practices have been taken into force for the agricultural sector (DÜV 2020). However, these regulations are heading primarily to fertiliser requirements of plants and do not or poorly specify limitations with respect to nutrient concentrations e.g. in the leachate or in groundwater. On the other hand, discharge from sewage plants are legally limited by concentration values, whereas international commitments to save the marginal seas consider specific reduction of loads in surface waters (e.g., HELCOM).

In countries like Germany, organised in federal states, reporting, source apportionment and quantification approaches, management practices, reporting forms and data presentations are done on various different hierarchical levels and require harmonisation across hydrological borders. Solutions across systems borders jointly supported by the main stakeholders (water management, agriculture, sanitary engineering and urban drainage) are required to achieve a good status of groundwater, surface waters and marginal seas. A common understanding of the nutrient inputs from the different sources, the resulting action requirements to meet the target values for the individual receptors and the measures to be taken to meet the environmental targets has to be developed. Integrated nutrient modelling are increasingly used to depict these complex interactions. In Germany a nationwide nutrient model system consisting of the RAUMIS-mGROWA-DENUZ-WEKU-MePhos-MONERIS models has been set up within the AGRUM-DE project to analyse the current situation and to develop and investigate scenarios reflecting the results of political and/or economical changes in the field of agriculture (Schmidt et al., 2020). The results will be used by the government of Germans Federal States for implementing agro-environmental measures to reduce nutrient pollution.

The multi-functional nature of woody buffers

As aquatic ecosystems are impaired by various stressors from different sources, also management options should be evaluated by their potentially multiple functions, to derive an optimum effect. Riparian buffers are widely discussed and applied in the context of river basin management and water quality improvement. In addition to nutrient and sediment retention, in particular woody buffers, in contrast to grass-covered ones, can provide a wide variety of functions, such as temperature/light regulation, habitat, and as landscape elements (provisional, regulating and cultural ecosystem services). Further, local and remote effects can be distinguished, i.e. the local effects to reduce nutrient emissions and the accumulative effects on loads at larger spatial scales. These functions are often evaluated separately and not jointly, as e.g. done in the EU-project OSCAR (http://www.freshwaterplatform.eu/index.php/oscar-tools.html), in order to derive new concerted management strategies.

For case studies in Germany and France, the effects of woody buffers are largest in small streams, where the share of surface runoff/erosion on total emissions is high and surface water can be completely covered from the canopy. In small streams, effects on water temperature are highly relevant, especially at low discharges and water depth, and daily maximum temperature can be reduced by up to 5°C. In addition, the reduction of total phosphorus is often of relevant scale, reducing emissions on average by 40% (Gericke et al., 2020) and concentrations by 20%. In larger rivers the local effects decrease due to increasing nutrient loads and heat energy fluxes. Surprisingly, local and upstream woody buffers showed small effect on river-type specific biodiversity of macroinvertebrates, indicating other pressures to prohibit or mask the positive effect of woody buffers in particular at larger scales. For these functions, it can generally be stated: “the-more-the-better”. In terms of ecosystem services an optimum solution depends on which balance of ecosystem services is preferred: the increase in cultural services, hence appreciation by recreation including anglers, comes at the expense of provisioning services, here particularly agriculture.

The project OSCAR tested a moderate and an ambiguous scenario under different climatic conditions. Until 2050, in one-quarter to one-third of the small streams, the increase in mean water temperature due to climate change can be compensated by the development of additional woody buffers in the ambitious scenario. Further research is needed to identify the causal pathways which and how pressures at larger spatial scales limit the potentially much higher effect of woody buffers on biodiversity.

Conclusions

Although intensively studied, there is still a need for continued research on diffuse pollution and its impacts on aquatic ecosystems. Rapid changes in developing countries and increasingly restricted legislation in many countries around the globe, combined with new, not yet well studied substances and altered by climate change, provide a challenging framework to manage and reduce diffuse pollution. Further, the still mostly linear present understanding of impacts from diffuse pollution and altered flow conditions on aquatic ecosystems has to be extended by a multiple stressor framework, leading to a much more complex picture on the needs of a successful management to reduce impacts on aquatic ecosystems. This, however, can also be applied to the management of agricultural and urbanised systems, as factors like globalisation, human well-being, or liveable environments under a growing world population have to be balanced.

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| 2.5 |

Disinfection

Part 1 – State of the art and future trends for disinfection technologies

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Current disinfection processes

Disinfection is an essential procedure in drinking water and wastewater treatment. Drinking water disinfection is an outstanding contribution for the protection of public health. Especially, chlorination of drinking water represents one of the greatest achievements in public health (Li and Mitch, 2018). In recent years, because of the diverse nature of human pathogens (viruses, parasites, bacteria, etc.), several disinfection technologies are often combined in so-called multi-barrier concepts. Some western European countries, such as the Netherlands, conduct another approach to restrain bacteria regrowth in drinking water distribution system by lowering down assimilable organic carbon (AOC) concentration as much as possible. This approach could avoid the disinfection by-products (DBPs) problem associated with the reaction between disinfectants and organic matter.

Wastewater disinfection is also very important to guarantee public health in relation to the microbiological quality of water body resources, especially for water reuse during the epidemic. Many pathogenic bacteria, viruses (enteric and respiratory) and protozoa can be transmitted and spread by faeces-mouth route. Consequently, free chlorine, chlorine dioxide or UV with higher doses have been applied in wastewater treatment plants (WWTPs) during the previous SARS epidemic and the current COVID-19 pandemic globally (formally called as novel coronavirus).

A global view on water and wastewater disinfection market identified five main disinfection technologies in terms of revenue, including chlorine-related technologies, UV, ozone, advanced oxidation process (AOP) and organic peroxy acids (Frost and Sullivan, 2018). In the following paragraphs, recent advances in consolidated technologies for disinfection are discussed.

Chlorine (Cl_2/NaOCl) and chloramines

Chlorine is still the most popular disinfection process in the water and wastewater industry around the world. In recent decades, more and more water utilities replaced liquid chlorine by stock or on-site generated sodium hypochlorite (NaOCl) in China and the USA because of safety concerns.

In terms of large-scale drinking water treatment plants (DWTPs), chlorine disinfection processes, including free chlorine and chloramines, are currently dominant. For example, the prevalent disinfectants used in the large-scale DWTPs (generally > 10^5 m^3/d) in Taihu Lake basin, Jiangsu province, China, are free chlorine and that used in Shanghai is chloramines. Generally, the selection of chlorine or chloramines mainly depends on source water quality, the water treatment processes, the occurrence of DBPs, including the regulated carbonaceous DBPs (C-DBPs) and unregulated nitrogenous DBPs (N-DBPs), and the requirement for residual disinfectant in distribution systems. The advanced treatment of ozone–biological activated carbon (O_3–BAC) integrated with conventional treatment process has been applied in Chinese DWTPs in recent years with the total capacity of 40 million m^3/d. This updating of DWTPs helps to address the water source pollution and improves the removal of many DBP precursors (Bei et al., 2019). Then, free chlorination or chloramination can be applied safely to avoid the violation of DBP regulation. Meanwhile, chlorine is also frequently added in the water intake, before and after coagulation, before and after filtration as oxidant to enhance coagulation, control algae and odor substances simultaneously in those DWTPs that suffer eutrophication in their water sources. Most recently, chlorination or electro-chlorination is used in the ballast water management systems (BWMSs) with an aim to reduce the biological matters to the extremely low levels

Keywords: Disinfection, disinfectant, chlorine, chlorine dioxide, ultraviolet, ozone, advanced oxidation process

regulated by the International Maritime Organization (IMO). Various evidences have demonstrated that chlorination works very well in the killing of zooplankton, phytoplankton and microorganisms (e.g., *E. coli*) with low energy consumption of around 100 kwh/ton of water to be treated. However, the formation and the presence of DBPs due to the operation may become an issue of concerns.

Chlorine dioxide (ClO_2)

Chlorine dioxide (ClO_2) is widely used as an alternative disinfectant to chlorine in water treatment. ClO_2 has been reported as being used in 8.1% of DWTPs in the USA and 32.8% of those in China (AWWA Water Quality Division, 2000; Zhang and Lu, 2016). Especially for Chinese DWTPs with small and medium scale (generally < 10^5 m3/d), ClO_2 disinfection accounts for a considerable proportion of about 70%. One of the great advantages of ClO_2 application is that its formation of regulated halogenated disinfection by-products (DBPs), such as trihalomethanes (THMs) and haloacetic acids (HAAs), is significantly lower than that of free chlorine (Barrett et al., 2000; Gates et al., 2009). Meanwhile, the formation of its specific DBPs, i.e. chlorite (ClO_2^-) and chlorate (ClO_3^-), is a major concern for ClO_2 application.

It is interesting to note that many applications of ClO_2 disinfection are actually combining ClO_2 with Cl_2 according to different generation processes. Compared with free chlorination, the combined ClO_2/Cl_2 disinfection system can reduce remarkably the sum of halogenated DBPs concentrations by decreasing Cl_2 percentages. The regulated trihalomethanes were reduced the most when ClO_2 was present, but the other individual DBPs group had distinct features with the variation of ClO_2 percentages (Zhong et al., 2019). The bromine and iodine substitution factors tend to increase with decreasing Cl_2 percentages, indicating that destruction of DBPs precursors by ClO_2 favored bromine and iodine incorporation. It was found that treatment of high ammonium-containing wastewater with ClO_2/Cl_2 exhibited considerable higher cytotoxicity potency than using single disinfectant (Zhong et al., 2019).

Ultraviolet (UV)

Ultraviolet (UV) irradiation has been increasingly applied to water and wastewater disinfection. One of its advantages – especially valuable in drinking water disinfection — is its high inactivation efficiency against *Giardia* and *Cryptosporidium*. Since no chemicals are added, the formation of DBPs can typically be avoided (Hijnen et al., 2006). Besides, some oxidants, such as H_2O_2, ozone, chlorine and persulfate, can be activated by UV irradiation to produce advanced oxidation processes (AOPs), which supply strong oxidising radicals to accelerate microbial inactivation and pollutant degradation (Anipsitakis and Dionysiou, 2004).

The USEPA Ultraviolet Disinfection Guideline for the final Long Term 2 Enhanced Surface Water Treatment Rule (UVDGM) was published in November 2006, in which three types of UV lamp were compared, as conclude in Table 2.2.

Table 2.2 Typical mercury vapor lamp characteristics

PARAMETER	LOW-PRESSURE	LOW-PRESSURE HIGH-OUTPUT	MEDIUM-PRESSURE
Germicidal UV light	Monochromatic at 254 nm	Monochromatic at 254 nm	Polychromatic, including germicidal range (200–300 nm)
Electrical to germicidal UV conversion efficiency (%)	35–38	30–**38** (35)	10–20
Arc length (cm)	10–150	10–**200** (150)	5–120
Lifetime (h)	8,000–10,000	8,000–**15,000** (12,000)	4,000–**9,000** (8,000)

Note: Modified from Table 2.1 in the UVDGM in which technical advances since 2006 are highlighted in bold with the original value in brackets.

In addition of producing more efficient and longer lasting lamps, the ageing factor (remaining UV output in % at the end of lamp lifetime) has been improved due to internal coating at nearly all low-pressure high-output lamps to values higher than 0.85. Furthermore, the variation of lamp output (standard for medium-pressure lamps) is now equally adopted by nearly all low-pressure high-output lamps. These developments in combination with design optimisations (due to CFD modelling and proven by performance validation) have led to a drastically reduced total cost of ownership (TOTEX) of UV disinfection systems mainly using low-pressure, high-output UV lamps – with UV systems requiring fewer lamps, lower energy and fewer lamp changes compared to 2006.

Ozone (O_3)

Owing to its oxidation potential, ozone is usually not used solely for disinfection but to further purify water and wastewater, e.g. removal of iron/manganese, elimination of odours and colours, degradation of micropollutants and emerging contaminants, which makes ozone an important tool in the overall treatment toolbox. It is typically combined with other disinfection technologies in the view of providing robust and resilient water and wastewater treatment. Most plants using ozone rely on dielectric barrier discharge ozone reactors, whose efficiency was significantly improved by the ozone industry in recent years.

Innovative disinfectants and processes

The following paragraphs address recent technologies that have not already been discussed.

UV LEDs

As LEDs revolutionised the (visible) lighting industry, the same can be expected for disinfection industry. At this stage, UV LEDs are expanding the market for UV disinfection as they are mainly used in conditions where conventional UV lamps would not be suitable or would not work effectively, especially in the point-of use water systems and consumer goods with disinfection needs. Their main specific advantages for these markets are as follows:

- mercury-free;
- configurable to suit special requirements (esp. tight spaces);
- no limitations in the on/off cycles (esp. valuable for discontinuous flows);
- immediately available (i.e. warm-up time);
- wavelength optimised for disinfection.

The pulsed mode and some specific wavelengths of UV LEDs have proved to be more effective on the inactivation of certain microorganisms (Li et al., 2010; Rattanakul and Oguma, 2018; Zou et al., 2019a). The wavelength adjustable UV LEDs provide possibilities for pollutants removal enhancement in the UV-activated AOPs (Rattanakul and Oguma, 2018; Zou et al., 2019b; Gao et al., 2019a, 2020). At this stage, combined with an electrical efficiency of about 5% and considerably higher costs per watt, UV LED systems are not yet competitive compared to conventional UV systems for higher flow municipal and industrial applications. However, considering their specific advantages in disinfection and further technological evolution, UV LEDs will become a promising alternative UV light in these areas.

Xenon excimer lamps

Another Hg-free light source are xenon excimer lamps. They have not entered the disinfection market with wavelengths in the germicidal region yet but Brueggemann et al. (2019) show another avenue for their use in the disinfection and oxidation market: narrow band VUV (vacuum ultraviolet) radiation from xenon excimer lamps with wavelength around 172 nm is ideally suited for ozone generation.

No nitrogen oxides or other deposits are formed by the VUV radiation, making the system very robust and eliminating feed gas issues. Extremely high ozone concentrations are achievable (up to 47 wt% from oxygen) thus reducing gas flows, decreasing capital expenses due to smaller systems and decreasing operational expenses induced by lower gas consumption.

Organic peroxy acids

Organic peroxy acids (or peracids) are a class of chemical compounds characterised by R-COOOH general molecular structure and strong oxidation potential. Two of these compounds are currently relevant as disinfectants, namely peracetic acid (PAA, CH_3CO_3H) and performic acid (PFA, HCO_3H). Among the benefits of these compounds there are wide-spectrum toxicity against pathogenic microorganisms, limited ecotoxicity, negligible or non-significant production of common DBPs (aldehydes, epoxides, halogenated DBPs, carboxylic acids, nitrosamines), as recently reported by Luukkonen and Pehkonen (2017) and Domínguez Henao et al. (2018a).

Organic peroxy acids are produced by reacting the carboxylic acid precursor with hydrogen peroxide in presence of sulfuric acid or other strong acids acting as catalysts. Because of their reactivity, PAA and PFA do not persist in the environment and quickly decompose into the precursor compounds. This is also a major reason preventing their use for drinking water. While PAA is provided in ready-to-dose commercial solutions that are quite stable under controlled conditions, PFA has to be produced on-site by means of dedicated systems. For both disinfectants, safety issues must be considered.

The poor stability of these disinfectants is also relevant for their application, since the decomposition rate increases with the presence of several compounds in water, indicating the importance of effective previous treatment processes (Domínguez Henao et al., 2018b, 2018c). Moreover, in relation to PAA instability, the benefits of monitoring, modelling and control techniques for optimising the disinfectant dosage depending on operating conditions and wastewater characteristics were reported by Manoli et al. (2019). In particular, it is worth stressing the importance of the actual dose calculation, namely accounting for disinfectant decay over time inside contact tank, in case of non-stable disinfectants, as organic peroxy acids.

Advanced oxidation processes (AOPs)

Advanced oxidation processes (AOPs) have been extensively AOPs have been extensively studied and some industrially developed over the last 15–20 years for the removal of mainly micropollutants but also disinfection. They all rely on the production at ambient pressure and temperature of oxidants having very high oxidation power such as hydroxyl radicals (•OH). Some relevant emerging AOPs for water and wastewater disinfection are presented below.

- **Electro-chlorination and electrochemical AOPs**

Electro-disinfection processes can be done mainly by mediated oxidation that produces oxidants (•OH, HClO, Cl_2, ClO_2, O_3) that play the role of disinfectants (Martinez-Huitle and Brillas, 2008).

The electrode material is an essential parameter to involve these disinfectants. Dimensionally stable anode (DSA) composed of mixed metal oxide (MMO) (e.g. Ti/RuO_2, Ti/IrO_2, Ti/Pt-IrO_2, Ti/RuO_2-IrO_2, etc.) have proven to be efficient to produce active chlorine disinfectant due to their high Cl evolution overvoltage (Jeong et al. 2009). Boron-doped diamond (BDD) have been also implemented as efficient anode to produce not only active chlorine but also hydroxyl radicals (•OH) that also demonstrated to be effective disinfectant (Bergmann et al., 2007). The amount of electro-generated disinfectants depends on the kind of electrolyte present in the solution. In presence of Cl^-, the quantity of oxidants is much higher than in other electrolytes (Na_2SO_4, $NaHCO_3$, and NaH_2PO_4). Still, oxidants can be produced in absence of $Cl^–$, and mainly with BDD material thanks to its high O_2 evolution overvoltage property. This is an advantage of advanced electro-oxidation over the electro-chlorination systems, though MMO materials are usually cheaper than BDD. Overall, the disinfection efficiency with electrochemical technologies over the chlorination system can be higher considering equivalent amount of oxidant dose, since different kinds of oxidants (chlorinated and non-chlorinated) can be produced simultaneously by reaching higher level of oxidation power (Mousset and Diamand, 2019).

The current density is another important parameter to control the rates and yields of disinfectants electro-generation. An increase of current density makes rising the concentrations until a certain extent, i.e. until the rate of secondary reactions (e.g. H_2O oxidation and reduction reactions) are competing too much with oxidant electro-generation reactions (Bergmann et al., 2007). However, the amount of potentially toxic by-products, e.g. the production of organo- and inorgano-chlorinated by-products in the absence of $Cl^–$ initially, tends to increase in the meantime (Bergmann et al., 2007). For example, it has been shown that perchlorate ($ClO_4^–$) was produced at a specific charge of 1 Ah/L, especially at high amount (123 mg/L) with BDD (Bergmann et al., 2009). Therefore, a compromise needs to be found between the optimum of oxidant electro-generation while avoiding/limiting the production of DBPs. It has been shown that applying a current density below 13 mA/cm^2 with BDD anode was sufficient for implementing electro-disinfection without generating perchlorate (Cano et al., 2011). At 1.3 mA/cm^2, the formation of chlorate and organo-chlorinated species could be also avoided, while only hypochlorite and chloramines were responsible for the disinfection process (Cano et al., 2011).

The disinfection efficiency of advanced electro-oxidation has been demonstrated for different kinds of water (Mousset and Diamand, 2019): municipal and industrial wastewater, seawater and ballast water, swimming pool water, washing water in agro-food & cooling water and process water. There have been some industrial applications, and most of the time the energy consumption could be ranged between 0.02 and 0.2 kWh/m^3 in conductive water, which was viable for industries (Mousset and Diamand, 2019).

- **Electro-pulse oxidation processes (EPOP)**

Recently Electrical Pulse Oxidation Process (EPOP) applying a high voltage, high pulse rate discharge, with O_2 as a carrier gas has been used as oxidising process to disinfect and also remove micropollutants from secondary treated effluents (Gafri et al, 2019). Electric discharges generated in liquids compared to plasmas in gases, require special conditions for their ignition due to substantially different properties of the ionised medium. Especially higher liquid density influences collision frequency of particles and thus the energy distribution as well. The discharge generation in liquids initiates various physical and chemical processes, which could be utilised in a wide spectrum of applications. Among physical processes, strong electric field, UV radiation, and a formation of shockwaves in highly conductive liquids are the most important phenomena. On the other side, a creation of various chemically reactive species such as •OH and other radicals, high energetic electrons, ions and molecules with high oxidation potential is the most usable chemical process.

The application of high electric energy into the system initiates an intensive movement of charged particles resulting in frequent collisions. The inelastic collisions lead to excitation and ionisation of neutral molecules. Finally, created plasma is formed by various charged particles, especially high energetic electrons, ions and radicals. This process (pulsed high voltage DC current for the discharge ignition), was piloted at a big

WWTP in Israel and the process was compared in parallel to ozonation in order to evaluate the process capabilities to reduce micro pollutants and disinfect at minimum DBPs. After optimisation of the EPOP process, (10–30 LPM O_2, 450–540 mA, 22–29 kV, 500–1000 Hz), to treat the secondary effluents, easily biodegradable trace organics and hardly biodegradable organics like X-ray contrast media were effectively removed. Micro-organisms such as: coliforms, fecal coliforms, fecal streptococci, *Giardia* and *Cryptosporidium*, viruses (entero-, adeno-, noro- and parecho-) were effectively removed from the secondary effluents. The total bacteria were low (120 CFU/ml) and no re-growth was observed. Almost no DBPs including NDMA and bromate was detected as compared to ozonation. The electrical energy use (as kWh/m^3) at one optimum work condition (15 LPM oxygen as carrier, 540 A, 28 V, 1000 Hz) to treat 1.8 m^3/h secondary treated wastewater was 0.25 kWh/m^3 (Gafri et al., 2019).

Besides, the EPOP process is also used in primary and secondary sludge treatment for disinfection, which brings a decrease in digested sludge volume (25%) and an increase in produced bio-gas (20%).

Monitoring, modelling and control for process design and management

Historically, disinfection design and management have been based on simplified relations and empirical knowledge. Although this approach is often appropriate, emerging challenges are highlighting the need for a paradigm shift in the view of improving process safety, reliability and sustainability, being innovative technologies a transformation driver. For example, biological stability preservation in drinking water distribution networks, DBPs minimisation in reclaimed wastewater and carbon footprint reduction in WWTPs impose the adoption of advanced approaches.

Since it is extremely complex to deal with the subject in depth, some essential emerging elements are presented and discussed in the following.

- Many sensors for real-time on-line monitoring of water microbiological quality, in terms of planktonic or biofilm microrganisms, are currently commercially available or under development. These instruments, that are based on multiple principles as flow cytometry (Safford and Bischel, 2019), enzimatic activity (Appels et al., 2018), fluorescence (Sorensen et al., 2018) and impedance (Turolla et al., 2019), can be effectively applied, alone or in combination with other conventional and innovative sensors for water chemical-physical quality, for overcoming constraints of established microbiological methods, namely scarse spatial resolution and measure delay.
- Modelling tools can be used to describe phenomena involved in disinfection at various scale, from very small ones, as for oxidative stress in bacterial cells, to relatively small ones, as for contact tanks, to much larger ones, as for water distibution networks or river basins. The definition of modelling setup (i.e. phenomena and governing equations, related variables and parameters, model structure and mathematical approach) usually depends on the objectives and changes significantly among different models. In case of disinfection reactors, for instance, models can be used to predict overall process performance, as for the well-established Integrated Disinfection Design Framework (Ducoste et al., 2001). In this case, kinetic equations for disinfectant decay, microbial inactivations and DBPs generation are solved over reactor residence time distribution in a zero-dimensional domain. On the other hand, when the objectives requires the local description of the system, modelling is usually based on Computational Fluid Dynamics (CFD) techniques, that allow solving the governing equations of involved phenomena, including fluid dynamics and mass transfer, in every sub-element into which the system is divided (Zhang et al., 2014). CFD is commonly used for optimising reactor design, especially in case of UV reactors (Jenny et al., 2015).
- The advances in monitoring and modelling paved the way for the development and application of control techniques with the aim of real-time optimised disinfection operation. In particular, control is essential for process safety and reliability in dynamic systems, where operating conditions change continuously over time (Manoli et al., 2019). System dynamic behavior can be extremely important for compliance on disinfection targets, possibly including conflicting elements, as microbial inactivation and DBPs generation.

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Disinfection

Part 2 – Disinfection-related challenges and opportunities

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Pathogens and related issues

Pathogens

Coliforms, total bacteria count, turbidity and residual disinfectants have been used as the indicators for biological safety of water and wastewater. Some countries regulate the pathogenic protozoa such as *Giardia* and *Cryptosporidium*. Few countries regulate the virus in water and wastewater treatment plants except that the USA included the treatment removal requirement for enteric viruses in the Drinking Water Standard. The normal water disinfection technologies, such as free chlorine, chlorine dioxide, ozone and UV have been reported as capable of inactivating viruses effectively. These disinfection technologies played important role in the great efforts to fight against previous global epidemics, including the SARS epidemic in East Asia 2003, the H1N1 epidemic in Mexico and USA 2009, the MERS epidemic in Middle East 2012 and the COVID-19 pandemic all over the world since December 2019. The main transmission routes for the viruses in aforementioned epidemics are respiratory droplet transmission and contact transmission, while fecal-to-oral pathway cannot be neglected. Therefore, it is very necessary to enhance disinfection in water treatment plants (WTPs), wastewater treatment plants (WWTPs). Meanwhile, strict quarantine measures and sufficient personal protecting equipment have been verified to be very effective to protect the operators and maintain the daily operation of WTPs and WWTPs in Wuhan, China, the first city to suffer from the severe COVID-19 pandemic (Wang & Qiu, 2020). Researchers also confirmed the high inactivation efficiency on SARS virus and SARS-cov-2 virus by free chlorine and chlorine dioxide (Wang et al., 2005; Hatanaka et al., 2021). Ozone, as a powerful gas disinfectant, can penetrate to the hidden area and inactivate the residual viruses well, which has been applied in large scale in food industries, transportation, especially for cold chain disinfection (Ma et al., 2021). UV application also increased greatly to improve the disinfection efficiency for water industries and others. Personal disinfection reagents, such as 75% alcohol solution and wipes, bleach have been widely applied in people’s daily lives.

Antibiotic-resistant bacteria and antibiotic-resistant genes

The discovery of antibiotics is one of the greatest medical achievements in the human history. In recent decades, antibiotics have also been commonly used in the livestock, poultry and aquaculture industries. However, the abuse and inappropriate discharge of antibiotics brought high concentration of antibiotics in some industrial and domestic wastewaters as well as the aquatic environment (Zhang et al., 2015). Accompanied by antibiotics, the problem of antibiotic resistant bacteria (ARB) and antibiotic resistance genes (ARGs) is also emerging all over the world, especially in developing countries.

Even for the drinking water industry, the concern on the toxicity of both ARB and ARGs cannot be totally neglected. ARB could be detected at 10^3–10^5 CFU/ml in polluted source water. Hundreds of species of ARGs were determined from source to tap water. The predominant ones, such as *sul*I, *tet*A, *erm*B, cml et al., could even be as high as 10^5 copies/ml. Since the antibiotics themselves are at trace level (ng/L or even lower) in drinking water, such low concentrations could not provide the selective pressure on ARB theoretically. Therefore, the occurrence and stability of ARB/ARGs might be associated with the characteristics of drinking water, e.g. oligotrophy. It was indicated that the oligotrophic condition limited the growing superiority of the wild-type strains over ARB, which meant ARB could avoid the “wash out” effect with the competence of the wild-type strains (Lin et al., 2018).

Another significant factor controlling the distribution of ARB and ARGs is the disinfection system. Standard disinfectants, such as chlorine, chlorine dioxide, ozone, can inactivate ARB and remove ARGs via strong oxidation. After chlorination and ozonation, both ARB and ARGs could be significantly reduced. ARGs could be decreased from 10^5-10^6 copy/ml to 10–10^4 copy /ml. Ozone, chlorine and chloramine can affect the cellular membrane permeability and lead to the leakage of cellular components. In addition, disinfectants can penetrate the damaged cells to directly oxidise the organelles. These functions are usually regarded as non-specific. With respect to extracellular DNA, chlorination was found to decrease the fluorometric signal of extracellular genomic and plasmid DNA by 70%, relative to a no-chlorine control.

The concern whether or not chlorination has a “co-selection” effect on ARB/ARGs has puzzled researchers for many years. The co-selection effect refers to the mechanism that adverse factors other than antibiotics, such as heavy metals, can select ARB together through some heavy-metal resistance genes, e.g. efflux pump. These genes can pump both heavy metals and antibiotics out of the cells. Some researchers suggested the enrichment of ARGs by chlorination (Shi et al., 2013). Other reports showed the negative results of no co-selection (Lin et al., 2016). Another interesting fact is the promotion of ARGs by mutagenic DBPs. The mutagenic DBPs, including MX, HAAs, HANs and bromate, could induce the resistance of *E. coli* and *P. aeruginosa* to ten categories of clinically-used antibiotics. The resistance could increase about ten folds maximum with 10 h exposure. The inducing ability of DBPs was consistent with the mutagenicity (Lv et al., 2014).

Biological and chemical stability in drinking water distribution networks

Drinking water disinfection issues include not only pathogen elimination but also bio-stability and corrosion control in the distribution system where disinfectants played an important role. Recent progress in the past 5 years is summarised as follows.

Biological stability in networks

As mentioned in the Disinfection Chapter of 2016 Global Trend Report, the biggest challenge for microbiological safety of drinking water may lie not in the water treatment plants but in the drinking water distribution system because of microbial regrowth over a long retention time. Microbial regrowth is mainly influenced by the residual disinfectant concentration and the carbon substrate (as determined by assimilable organic carbon (AOC) or biodegradable dissolved organic carbon (BDOC)), while temperature, flow, and phosphate concentration have been also regarded as limiting factors in some studies (Szabo and Minamyer, 2014).

The World Health Organization (WHO) stated that “water entering the distribution system must be microbiologically safe and ideally should also be biologically stable”. To achieve the goal of biostability, two different approaches are conducted around the world. Many countries require to maintain the residual disinfectant to restrain bacterial regrowth in pipes. For example, US EPA suggests that the residual disinfectant be measurable in the taps. Moreover, about 20 states in the USA set the minimum level of residual chlorine concentration over 0.2 mg/L. China requires 0.05 mg/L of chlorine/chloramine or 0.02 mg/L of chlorine dioxide at the end of distribution system. Another approach is to lower the AOC concentration as much as possible to starve the bacteria. An AOC value less than 10 µg C/L was proposed to achieve biologically stable drinking water in the Netherlands where chlorine disinfection was abolished (Ohkouchi et al., 2013).

Chemical stability

Chemical stability problem is closely related with disinfection since residual disinfectant is very important for corrosion and scale formation. Change of disinfection process and change of water source are the main causes of chemical stability all over the world. For example, the residents in Washington, D.C., USA experienced lead release in tap water in 2010 after the chloramination was applied to replace free chlorination for the control of trihalomethanes and haloacetic acids. A weak disinfectant will lower the redox potential of pipe system and the stable lead oxide (PbO_2) will be reduced to soluble and toxic lead ion (Zhang and Lin, 2013; Guo et al., 2014).

In 2016, the report on the elevated blood lead levels in the children associated with the drinking water of Flint, Michigan revealed the severe problem of water stability in this water utility (Hanna-Attisha et al., 2016). The immediate cause of the high water lead levels was the destabilisation of lead-bearing corrosion rust layers that accumulated over decades on a galvanised iron pipe downstream of a lead pipe (Pieper et al., 2017). This emergency issue was initiated by changing the source water into a highly-corrosive source water and the failure to treat this water properly. Besides lead increase, colored water, trihalomethane (THM) violation, more detection of *Legionella* also occurred after the change of source water. The lesson from Flint should be regarded seriously by water professionals all over the world (Masten et al., 2016).

Coloured water events are found to occur sporadically in China since many cities are facing the shortage of local water sources and relying on the long-distance transportation of water (Zhang et al., 2014). Increase of corrosive anions, i.e. sulfate and chloride and decrease of alkalintiy and pH were observed to affect iron release. Some bacteria are reported to be associated with scale dissolution and iron release. Moreover, the introduction of desalinated water will also increase the possibility of coloured water due to the sharp rise in the Larson ratio of chloride concentration to alkalinity. Thus, the careful blending of different source waters, the increase of pH or alkalinity, higher dosage of free chlorine, and addition of orthophosphate were investigated and applied to address these events (Zhang et al., 2014).

Identification and control of emerging DBPs in drinking water

Emerging DBPs

Even though more than 800 disinfection by-products (DBPs) have been identified, more than 60% of total organic halogen (TOX) still remains unknown (Richardson, 2002; Yang et al., 2016). Thanks to the development of analytical technology, more emerging DBPs have been identified and detected in drinking water, swimming pool water, and wastewater. Emerging DBPs can be dived into three main groups according to their molecular structures: 1) aliphatic DBPs; 2) alicyclic DBPs; 3) aromatic DBPs. Most aliphatic DBPs including haloaldehydes (HALs), haloacetonitriles (HANs), halonitromethanes (HNMs), and haloamides (HAMs) share a simple 'CX_3-R' molecular structure, which have been termed 'CX_3R-type' DBPs (Yao et al., 2018; Ding et al., 2019). Those three types of DBP can be further divided into nitrogenous DBPs (N-DBPs) and carbonaceous (C-DBP) according to their functional groups. Besides, emerging DBPs with bromide or iodide substitution are generally referred as Br-DBPs or I-DBPs, which have attracted much attention due to their relatively high toxicity (Dong et al., 2019).

For emerging DBPs which occur at trace level, high fold pre-concentration pretreatment such as solid-phase extraction may be needed to achieve a lower detection limit (Yang and Zhang, 2016; Ding and Chu, 2017; Yang et al., 2019). Gas chromatography (GC)-related methods play an important role in the identification and quantification of volatile or semi-volatile emerging DBPs which include most CX_3R-type DBPs and several aromatic DBPs (Ding and Chu, 2017; Zhang et al., 2018). Liquid chromatography (LC)-related methods are more suitable to analyse non-volatile emerging DBPs. After separated by GC or LC, emerging DBPs are then analysed by detectors such as MS, tqMS and QTOF-MS. Generally, emerging DBPs are identified by matching retention time, isotopic patterns and mass spectra (Yang et al., 2019). If the molecule have already been identified, quantification can be made based on the peak area on the specific retention time in the chromatogram, and other detectors such as electron capture detector and UV detectors may also be applied (Ding and Chu, 2017).

Great effort has been made on the control of emerging DBPs. Generally, emerging DBPs control is mainly achieved by 1) removing precursor before disinfection, 2) optimising disinfection process and 3) eliminating the formed DBPs. However, there is no single solution that can simultaneously reduce the formation of all emerging DBPs. Thus, cautious trade-off should be made when any emerging DBPs control strategies are applied, and the variation of overall toxicity rather than specific groups of DBPs should be paid more attention (Han and Zhang, 2018). Common water treatment processes including coagulation and filtration are typically rather ineffective for removing the precursor of emerging DBPs (Bond et al., 2011). Therefore, advanced water treatment processes including AOPs, activated carbon adsorption and membrane filtration may be needed (Hu et al., 2018). Even though there is no disinfectant that can avoid DBPs formation, the disinfectants type, dose and contact time can be optimised to reduce the health risk caused by emerging DBPs (Ding et al., 2019). Since DBPs formation is inevitable, some method such as UV irradiation or iron reduction may also be of help to reduce the overall toxicity (Chu et al., 2016; Huang et al., 2019). A better emerging DBP control efficiency may be achieved by combination of those methods.

Nitrosamines

N-nitrosamines are a family of emerging nitrogenous DBPs with high carcinogenicity, and frequent occurrence in disinfected drinking waters and wastewaters in many countries (Krasner et al., 2013), especially in Canada (Charrois et al., 2007; Zhao et al., 2008), USA (Russell et al., 2012), Australia (Linge et al., 2017) and China (Bei et al., 2016). N-nitrosamine regulations and guidelines in drinking water throughout different parts of the world have been advanced as a result of their perceived toxicology and occurrence at levels of health concern (WHO, 2017). Ontario, Canada, first regulated nitrosodimethylamine (NDMA) in drinking water of 9 ng/L in 2002, followed by Massachusetts, USA, in 2004 (10 ng/L) and California, USA (10 ng/L). The WHO included NDMA with the level of 100 ng/L in the Guidelines for Drinking Water Quality in 2008 which is accepted by Australia. Canada promulgates the first and so-far the strictest national standard for NDMA (40 ng/L) in 2010 (Kristina et al., 2012). Some leading cities in China, such as Shanghai, Shenzhen and Suzhou, set up the local water quality standards for drinking water since 2018 and their criteria for NDMA is 100 ng/L.

The basic strategies to control nitrosamine formation in drinking water include the removal and/or destruction of nitrosamine precursors and/or optimisation of the chloramination conditions (Krasner et al., 2013). The performance of conventional processes in controlling nitrosamines is quite limited, especially when the polymer flocculant, i.e. polyDADMAC is used. Strong oxidants other than chloramines, including free chorine, ozonation (Lee and von Gunten, 2010), and chlorine dioxide have been shown to destroy/transform secondary or tertiary amines and NDMA precursors. Powdered and granular activated carbon (PAC and GAC) have been shown to remove wastewater-derived NDMA precursors effectively (Hanigan et al., 2012). The combination of conventional and ozone–biologically active carbon (BAC) processes has been widely applied in drinking water treatment to enhance the removal of dissolved organic matter and DBP precursors (Liao et al., 2015a; Bei et al., 2019). However, in some cases, bacteria and soluble microbiological products from the biofilter constituted a source of NDMA precursors (Liu et al., 2017). The general structure of nitrosamine precursors, i.e. a positively charged dialkylamine group and the non-polar moiety, explains the mechanism of nitrosamine precursor removal by these processes (Chen et al., 2014; Liao et al., 2015b). This structure inspired the researchers to develop the cation exchange technology to remove the positive-charged NDMA precursors (Li et al., 2017).

Dozens of nitrosamine precursors have been identified until now, including secondary amines, water treatment coagulants, pharmaceutical and personal care products, pesticides, organic matter in wastewater treatment plant effluents, certain industrial chemicals, algal organic matter, and natural organic matter. However, the specific chemicals as predominant nitrosamine precursors in wastewater treatment plant effluents have not been identified.

Inorganic DBPs

Chlorite yield was found to be dependent on the distribution of functional groups of organic matter (Gan et al., 2019a). The reaction between chlorine dioxide and amines, di- and tri-hydroxybenzenes exhibited chlorite yields over 50%, indicating that one-electron transfer pathway was the dominant reaction mechanisms. Oxidation of olefins had chlorate yields around 50% and reactions involving HOCl and other intermediate species seemed to get involved in its formation. Oxidation of thiols had the highest chloride yields (~32%) because of their high reduction potential to be able to further reduce chlorite (Gan et al., 2019). Chlorite yields from humic substances depended on the chlorine dioxide dose, pH and varied with different reaction intervals, which mirrored the behavior of the model compounds. Phenolic moieties served as dominant fast-reacting precursors (during the first 5 min of disinfection). Aromatic precursors (e.g., non-phenolic lignin or benzoquinones) contributed to chlorite formation over longer reaction times (up to 24 hours) (Gan et al., 2019b). The total antioxidant capacity (indication of the amount of electron-donating moieties) determined by the Folin-Ciocalteu method was a good indicator of chlorite reactive precursors in humic substances, which correlated with the chlorine dioxide demand of waters. Waters bearing high total antioxidant capacity tended to generate more chlorite at equivalent chlorine dioxide exposure, but the prediction in natural water should be conservative.

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| 2.5 |

Disinfection

Part 3 – Health concerns of disinfection-related issues

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Risk-based approaches

Recent regulations related to water are promoting risk-based approaches for the management of drinking water and wastewater microbiological quality, as in the case of the proposed revision of the drinking water European Directive 98/83/EC (The European Parliament and the Council of the European Union, 2018). Moreover, the relevance of such approaches is progressively increasing due to the increasing need for direct and indirect water reuse determined by climate change. Risk-based approaches basically consist in the risk assessment along water supply and wastewater treatment systems, in the view of prioritising risks and adopting effective risk management control measures. Risk-based approaches are constitutive elements of Water Safety Planning and Sanitation Safety Planning, as described in World Health Organization (WHO) manuals (WHO, 2009; WHO, 2015).

About 20 years ago, Quantitative Microbial Risk Assessment (QMRA) emerged as a reliable methodology for evaluating the potential risks of contamination from pathogens (Haas et al., 1999). Such methodology has been successfully applied to drinking water supply for several goals, including risk assessment related to drinking water distribution system management (Blokker et al., 2017). Similarly, it has been used for wastewater management, as for estimating the risk related to wastewater agricultural reuse (Moazeni et al., 2017). Currently, two main trends are evident for QRMA development: on the one hand, the integration of QMRA in user-friendly tools, that could promote its use among non-experts, as QMRA Treatment Calculator by Watershare; on the other hand, QMRA is being more and more integrated with decision support systems for the management of water resources and with water and wastewater treatment control systems (Beaudequin et al., 2016).

Health concerns about disinfection and DBPs

Access to safe drinking water is a basic human right and a component of effective policy for health protection. On the one hand, the application of disinfection in water treatment significantly vanquished the outbreaks of cholera, typhoid and other waterborne diseases. On the other hand, low but significant associations between disinfected drinking water consumption and adverse health effects have been demonstrated, including cancers of the bladder, colon and rectum, as well as adverse pregnancy outcomes and developmental effects (Hrudey, 2009; Diana et al., 2019). The chronic risks posed by exposure to DBPs became a sensitive but important issue, including cytotoxic, genotoxic, mutagenic, teratogenic, carcinogenic, endocrine disrupting effects and other toxicological effects (Sun et al., 2019).

Wagner and Plewa (2017) provided the methodology for the quantitative, comparative analyses on the induction of cyto- and genotoxicity of 103 DBPs using Chinese hamster ovary (CHO) cells. They represented the largest direct quantitative comparison on the toxic potency of both regulated and emerging DBPs based on the published data and additional new results. However, the large gap between epidemiological and toxicological studies remains. Only insufficient evidence has been found to determine the carcinogenicity of individual DBP, particularly of plausible bladder carcinogens (Diana et al., 2019). This discrepancy may be attributed the unidentification of responsible DBPs, including their occurrence in drinking water and toxicity characteristic; the assessment of individual chemicals or simple mixtures instead of complex mixture, which is more realistic and could represent the synergistic toxicological effects; as well as the exposure assessment limitation associated with different exposure route (e.g., ingestion, dermal contact and inhalation) and spatiotemporal variations in DBPs concentration (Li and Mitch, 2018; Diana et al., 2019).

As a consequence, firstly, the identification of new priority DBPs in drinking water and health effect assessment based on concentration and toxicity should be given more attention. For instance, Zhang et al. (2018) identified chlorophenylacetonitriles (CPANs), a new class of nitrogenous aromatic DBPs in drinking waters. However, compared with aliphatic counterparts, CPANs were much more stable under the same pH conditions, both in the presence and absence of Cl_2 or NH_2Cl. CPANs are more cytotoxic than the corresponding haloacetonitriles, with the evidences reported for the finished drinking waters (Richardson and Kimura, 2020). Secondly, additive or synergistic toxicological effects are of importance, including different DBPs and other micropollutants. For example, Hu et al. (2018) compared the different treatment processes combinations with the calculation of overall cytotoxicity and genotoxicity based on the formation and toxicity of selected DBPs during subsequent chlor(am)ination in order to design the optimised treatment processes in drinking water treatment plants. Lastly, the assessment of public health impacts of DBPs is supposed to use appropriate data, modelling and assumptions (Grellier et al., 2015), and the spatiotemporal variation of DBP concentrations, the formation and transformation of DBPs in distribution and plumping systems and the exposure approach other than ingestion should be taken into account when assessing DBPs effect to human health (Weinberg et al., 2006; Villanueva et al., 2011).

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| 2.6 |

Groundwater restoration and management

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Groundwater in urban water supply

Groundwater already plays a critical role in urban water-supply, globally providing in the order of 50% of all supplies, but all too widely is overlooked at the resource management level. As a result today, in and around cities, groundwater resources are often the subject of irrational exploitation and contaminant loading that threaten their sustainability through depletion and pollution. Urbanisation greatly modifies the 'groundwater cycle', and the associated problems can be costly and persistent. While many of these problems are 'predictable' few are actually 'predicted', and have serious implications for human health and well-being.

Climate change is widely predicted to impact water resources, and making better use of groundwater stored in aquifers can offer a decentralised, cost-effective solution for climate-change adaptation at the scale of specific cities. (Foster, Gathu, Eichholz, & Hirata, 2020). The 2017-2018 Cape Town water-supply crisis provides a classic example of the type of situation that can arise under climatic stress where a major municipal utility relies exclusively on large surface-water reservoirs and has not diversified its sources to include local groundwater systems. In June 2017 the storage of its largest reservoir fell to below 15% and a domestic supply restriction of 100 lpd/capita was imposed, with subsequent reductions to 50 lpd/capita a few months later, and a warning that the situation was fast approaching when all domestic taps would have to be shut-off. (Foster, Eichholz, Nlend, & Gathu, 2020).

Groundwater resources offer the possibility of improving urban water-supply resilience to protracted drought at modest capital cost. They are thus a critical element when it comes to facing the challenge of climate-change adaptation – but urban water-utilities will need to take a more proactive approach to groundwater resource management and quality protection if this critical role is to be sustainably secured.

State of current understanding

Increasing dependence on groundwater

There is considerable evidence to suggest increasing dependence on groundwater for water supply in developing cities. This is occurring in response to population growth, accelerated urbanisation trends, increasing per capita use, higher ambient temperatures and reduced security of river-intakes, and is facilitated by the generally modest cost of waterwells. Unfortunately there are no systematic, comprehensive data to quantify this trend, but it has been approximately estimated that more than 1,500 million urban dwellers worldwide currently rely on groundwater.

Those urban centres underlain and/or surrounded by high-yielding aquifers, of sufficient potential to provide a major component of utility water-supply, usually have better mains water-service levels and lower water-prices. This allows utilities to expand their water-supply production incrementally at relatively low cost in response to rising demand. However, there are rarely sufficient groundwater resources within the urban area itself to satisfy the water-supply demands of larger cities, and resource sustainability often becomes an issue. Moreover, groundwater quality may also be threatened by inadequately-controlled urban pollution pressures. *In situ* sanitation of major urban areas presents a significant groundwater quality hazard, which needs to be recognised and systematically managed. In most aquifer types (except the extremely vulnerable) there will be sufficient natural attenuation to eliminate faecal pathogens in percolating wastewater from *in situ* sanitation, but elevated concentrations of nitrate and DOC will arise to varying degree according to the population density served by *in situ* sanitation.

Groundwater development normally has relatively low capital

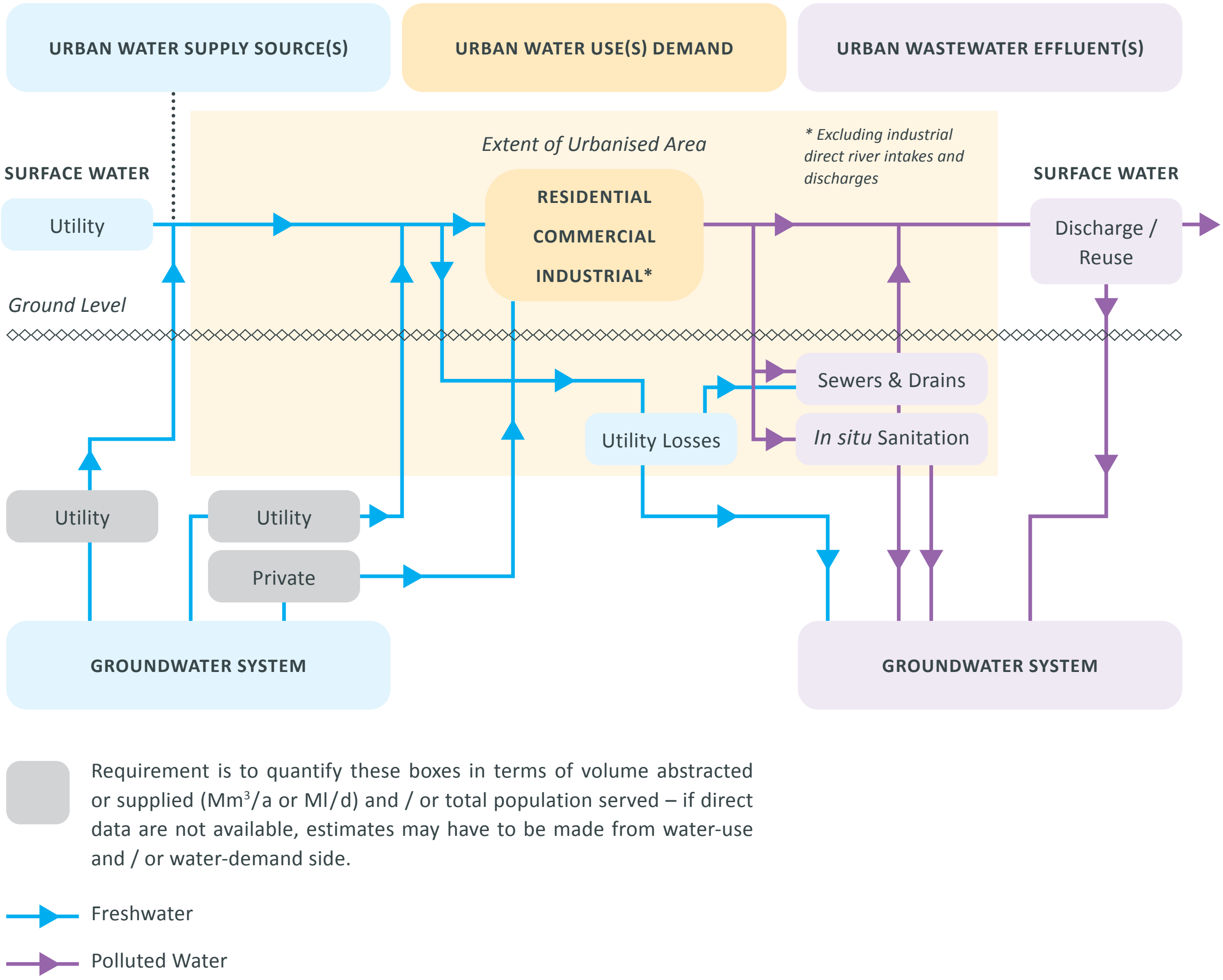

Figure 2.2: Urban groundwater processes in cities underlain by unconfined aquifers (Foster, Gogu, & Gathu, Urban groundwater – mobilising stakeholders to improve monitoring, 2019)

and operational costs, (Foster, Eichholz, Nlend, & Gathu, 2020) which is a consequence of being for the most part of good quality and not requiring advanced treatment. A further potential advantage is that in many cities groundwater is widely distributed, making it possible to develop utility waterwells cheaply and rapidly as the 'hub' of new decentralised closed-loop systems of water-service provision for rapidly-developing outer districts with populations of 20,000–50,000.

Urban groundwater use includes not only withdrawals by water-utilities, but also by many categories of private users. *In situ* residential self-supply from groundwater is a 'booming phenomenon', especially in South Asia, West Africa and Latin America, and widely represents a significant proportion of the water actually received by users. The practice is primarily the solution of those with higher incomes, but can have serious implications for the following

- planning and investment in public water-supplies, seriously decreasing the income of water-service utilities and impacting their ability to recover investment to subsidise 'social tariffs';
- public health, where private waterwells are inadequately constructed and/or sited with respect to *in situ* sanitation units or other potential-pollution sources. (Foster, Eichholz, Nlend, & Gathu, 2020).

Groundwater hazards

The principal hazards confronting urban waterwell use are as follows

- frequent groundwater quality degradation from inadequate *in situ* sanitation, leaky storage of hydrocarbon fuels and casual disposal of industrial effluents to the ground; such pollution normally impacts private waterwells preferentially (as a result of their shallower depth and typical locations) but persistent contaminants (such as nitrates and some synthetic organic industrial and community chemicals) persist to greater depths and pollute utility waterwells;
- a tendency to over-exploit groundwater resources within urban areas where the water-utility is a major abstractor, which can be accompanied by land subsidence impacting the urban infrastructure and saline-water intrusion especially in coastal settings. (Foster, Eichholz, Nlend, & Gathu, 2020).

Many peri-urban settlements are not formally planned, and lack legal recognition and city planning procedures, and thus water-utilities are often reluctant to extend their networks because of anticipated high cost and low revenue. Thus poor peri-urban communities can only gain direct access to groundwater where

- community-based organisations use social capital and political connection to secure funding for non-reticulated waterwells from government programmes;
- non-governmental organisations provide non-reticulated waterwells (sometimes in association with water-utility pro-poor departments) to supply collection standposts;
- low-cost dugwells can be constructed to tap an exceptionally shallow water-table, although these have the handicap of being much more vulnerable to contamination.

Where the urban environment is concerned, ‘one person’s solution tends to become another person’s problem’. All too often there is a vacuum of responsibility, and therefore of accountability, for urban groundwater – with at best responsibility being split between a number of organisations none of which take a lead in coordinating necessary management actions. These organisations can include: municipal water-service utilities, provincial/state government water-supply and public-health engineering departments, central and/or provincial/state/basin groundwater resource agencies and environment protection/pollution control agencies. Groundwater use sustainability is greatly influenced by a complex array of local developmental decisions, which are rarely viewed in an integrated fashion, including

- production and distribution of water-supplies (by municipal water-service utilities and public-health departments);
- urbanisation and land-use planning (by municipal government offices);
- Installation of sewered sanitation, disposition of liquid effluents and solid wastes (by environmental authorities, public-health departments and municipal water-service utilities).

Policy actions

Policy actions are required to ensure sustainability of the groundwater resource base, including the following

- definition of areas with critical levels of resource exploitation as a basis for restricting further development;
- providing clear criteria by area for issuing of waterwell permits (in terms of safe separation and maximum pumping rates);
- controlling municipal and private groundwater abstraction on the basis of defined areas – including the relocation of municipal waterwells, increased resource-use fees, and (even) closure of private waterwells where local conditions so merit.

In cities with high dependence on groundwater it is usually a good idea to pursue all reasonable opportunities for aquifer recharge enhancement, through rainwater harvesting and infiltration from roofs and paved areas, and collection of flood runoff to recharge ponds.

The establishment of municipal wellfields outside cities, with their capture areas being declared ecological or drinking-water protection zones, must be promoted as ‘best engineering practice’. Their promotion often encounters impediments related to fragmented powers of land-use and pollution control between the numerous municipalities that usually comprise ‘metropolitan areas’. Incentives need to be established for the groundwater resource interests of a given urban municipality to be assumed by a neighbouring rural municipality, such that adequate protection can be offered for the capture area of an ‘external municipal wellfield’.

Groundwater is widely far more significant in water-supply of cities and towns than is commonly appreciated and is also often the ‘invisible link’ between various facets of the urban infrastructure. Regretfully organisations concerned with urban water-supply and environmental management often have a poor understanding of groundwater – and this needs to be corrected.

Future trends & challenges

There are a number of key policy issues that require much more attention, as appropriate to the situation in industrialised or developing nations. Effort must be put into synthesising and disseminating positive practices on the following

- mobilisation of water-service utilities as major stakeholders in groundwater resource management and protection – controlling use, conserving quality and enhancing recharge;
- development of groundwater storage to improve water supply security within climate-change adaptation plans;
- rationalising and integrating the phenomenon of large-scale private self-supply from groundwater in many developing cities;
- identification of the role of groundwater as a ‘major cross cutting element’ in the implementation of integrated water resource management strategies thereby making the invisible visible;
- promotion of groundwater monitoring to provide the baseline information essential for sound decision-making in engineering construction and environmental management;
- improvement of groundwater and waterwell data management to serve as a basis for assessing trends and guiding future abstraction plans.

The consequences of non-action on these policy essentials will be felt in terms of much increased exposure to water-supply crises, potentially-hazardous pollution incidents, and irrational public and private investment in water-supply access.

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| 2.7 |

Health-related water microbiology

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Introduction

Health-Related Water Microbiology (HRWM) is one of the Specialist Groups of the International Water Association (IWA). Our group was the first of the specialist groups, installed in 1977 as the Water Virology Specialist Group (within the former IAWPRC). The Specialist Group is a forum for the exchange of scientific information in the field of health-related water microbiology. This encompasses many fields of expertise: from environmental to clinical virology, bacteriology and parasitology, from infectious diseases epidemiology to risk assessment methodology; from water treatment engineering to environmental health practice. Here we report the recent progresses in the field of health-related water microbiology.

Risk assessment and guideline development, and the global water pathogen project

The SG has been involved in the application and improvement of microbial risk assessment for several years. The group has specifically applied the risk assessment tool to develop risk-based water quality guidelines and standards for microbial water quality. Over the years, experts from the group formed part of WHO working groups to develop risk-based guidelines. Guidelines are revised or updated every number of years to include recent knowledge on new and emerging pathogens or improved technologies and the latest detection methods. Guideline development is increasingly risk-based making use of electronic decision support systems. For example, the Water Research Commission under auspices of the Department of Water and Sanitation in South Africa recently funded a research initiative to revise the South African water quality guidelines (e.g., recreational water, drinking water, irrigation water). The specific focus was to develop risk-based guidelines together with an electronic decision support system which could be used by water managers to make informed decisions and manage risks.

One of the leading projects in this area is the global water pathogen project (GWPP). The GWPP aims at developing a knowledge resource to reduce mortality and morbidity linked to water pathogens and the lack of safe drinking water and basic sanitation through creating the state-of-the-art knowledge hub on water-related disease risks and intervention measures. The GWPP is now being translated into IT tools to help improve data accessibility, and knowledge translation around pathogens in excreta and sewage. Specifically, the project members are developing apps and visualisation tools that can help to improve evidence-based decision making and to better inform safe sanitation and water safety planning by stakeholders at different levels. This project is known as the water knowledge to practice project (Water-K2P), and it is funded by the Bill and Melinda Gates Foundation. The Water-K2P project will support water and sanitation safety planners in using an evidence-based approach for managing health outcomes by improving access to scientific data on the efficacy of sanitation technologies and the occurrence and persistence of pathogens in human excreta and sewage. This project will establish a coalition of national and local stakeholders in Uganda as the first partners and develop analytical information and communication technology (ICT) tools for estimating loads of waterborne pathogens, selecting sanitation technologies to ultimately help support decision-making for safe sanitation. This project will accomplish these tasks by leveraging the open access knowledge resources generated by the GWPP (*www.waterpathogens.org*).

General trends and challenges

Next generation sequencing techniques in water microbiology

The study of microbial diversity as well as the identification of new strains in different environments has been enhanced by using the next generation sequencing (NGS) technology that can detect a wide range of microbial populations in a given sample. Several studies have demonstrated that sewage reflects the bacteriome, virome and parasitome excreted by human populations. Illumina sequencing platforms have been widely adopted as the sequence platforms of choice for NGS due to lower per-base costs and error rates and greater data output in comparison with other platforms (Chan et al., 2019). In combination with metadata, NGS data will also allow the identification of drivers of microbial community composition in water treatments and distribution networks, facilitating monitoring of bacterial regrowth and contamination in technical systems.

Different studies have also characterised virus, bacteria or protozoa diversity in groundwater, river water and reclaimed water and a recent study has analysed the virome, bacteriome and parasitome of irrigation water, analysing distribution potable water, superficial and ground water (Rusiñol et al., 2020). It is now known that target enrichment NGS protocols increase the sensitivity for the characterisation of viral pathogens and amplicon deep sequencing provides high-resolution analysis into community composition in complex water matrices such as urban sewage (Martinez-Puchol et al., 2020) being a valuable tool for monitoring microbial communities or specific viral groups in natural as well as technical aquatic systems.

Recent activities in the evaluation and application of microbial source tracking (MST) marker

Most studies using MST marker genes by quantitative polymerase chain reaction (qPCR) enumeration were valuated/applied in relatively small catchments or watersheds. However, studies have become increasingly available on applying or evaluating MST qPCR diagnostics on a continental or even global scale. For example, one MST application was successfully applied on the whole navigable River Danube in Europe, including a range of more than 2500 km. By combining standardised fecal indicator bacteria and MST qPCR diagnostics human as the dominant source of fecal pollution could be identified (Kirschner et al., 2017). Recently, human- or sewage-associated MST qPCR diagnostics were also evaluated on a global scale in 13 countries from 6 continents in urban and rural wastewater treatment plants. It was demonstrated that bacterial human-associated MST markers based on bacterial targets occurred universally and in high concentrations in raw and biological treated wastewater (Mayer et al., 2018). This is a crucial prerequisite in the universal application of MST markers.

Developing alternative and simpler detection diagnostics for MST targets

The qPCR has become the favorite tool for the enumeration of genetic MST targets during the last decade. However, qPCR methodology requires well equipped laboratory infrastructure and specialised personal. Recently, isothermal amplification methods (ISOAMP) has been suggested as possible alternatives to PCR, with potential for high-throughput screening or rapid detection (Martzy et al., 2019). It was recently demonstrated that MST markers could be rapidly detected by isothermal helicase-dependent amplification combined with a nucleic acid lateral flow strip test (Kolm et al., 2019). Using rapid sample filtration and DNA-extraction procedures combined with ISOAMP methods hold great promise to support the application of MST assays also in low resources settings or in field applications in the near future (Martzy et al., 2019).

Integrating information from MST targets in water quality simulation models

As manifested in the Rotorua Declaration, there is a need to integrate information from microbiological diagnostics into water quality models for improved prediction and simulation in water safety management. A recent modelling effort demonstrated the use of multi-parametric information from fecal indicators and MST markers for the enhanced prediction on the source of fecal pollution (Ballesté et al., 2020). A human-associated MST marker was also successfully used to specifically calibrate a catchment-based quantitative microbial risk assessment (QMRA) model to a specific river location in order to predict the required treatment capacity (i.e. LRVs, log reduction values) for the production of safe drinking water (Derx et al., 2016).

Bacteriophages as indicators of enteric viruses and fecal contamination

In the past several decades, bacteriophages, especially somatic and F-specific coliphages, have been traditionally used as surrogates of enteric viruses in numerous laboratory-scale as well as real-scale studies, such as (waste)water treatment and disinfection experiments, because of their morphological and biological similarities with enteric viruses. They are also considered potential indicators of contamination of enteric viruses in the aquatic environments. Main viruses of concern have shifted gradually from cultivable viruses, such as enteroviruses, to non-cultivable viruses including noroviruses, for which efficient culture systems have not yet been established. However, these cultivable bacteriophages are still considered and accepted as suitable surrogates and/or indicators of enteric viruses (Jofre et al., 2016; McMinn et al., 2017). Actually, for example, somatic coliphages are currently used in water quality guidelines for water reclamation, groundwater, etc. in some countries and regions.

Somatic coliphages are easily cultured using a host strain, such as *Escherichia coli* WG5, within a period of 24 h, but more rapid and simple techniques are required to establish nearly real-time monitoring of microbial water quality to adequately control the risk of pathogen infection via contaminated water and/or to assess fecal contamination of the environments. A recently developed method, *Bluephage*, which utilises a modified *E. coli* strain with knocked-out *uidB* and *uidC* genes, enables to detect as low as one somatic coliphage in a sample within 3.5 h (Muniesa et al., 2018). This culture-based assay has a great potential to be used widely for routine monitoring under various situations.

F-specific RNA (F-RNA) coliphages have been used not only as surrogates of enteric viruses but also as indicators of fecal contamination of water. Among four genogroups (GI-GIV) of F-RNA coliphages, GII and GIII are generally excreted with human feces, while GI and GIV are excreted with animal feces, which have supported the applicability of using F-RNA coliphages as fecal contamination indicators. However, the increasing number of studies have reported exceptional cases in which, for example, GII and GIII can be detected in animal feces, suggesting that simple detection of F-RNA coliphage genogroups is inadequate to be used in MST approach.

Another recently proposed possibility is to use certain F-RNA coliphage genogroups in microbial water quality management. For example, GI F-RNA coliphages are found more resistant against conventional wastewater treatment than not only other genogroups (GII–GIV) but also most of enteric viruses, indicating that GI F-RNA coliphages can be a suitable indicator of virus reduction during wastewater treatment process (Haramoto et al., 2015). GII F-RNA coliphages are suggested as a potential indicator to estimate contamination levels of noroviruses in oyster (Lowther et al., 2019). Conventional plaque assay does not provide any information about the abundance of each of the four genogroups; thus, reduction and survivability of F-RNA coliphages determined by plaque assay can vary depending on the type of the abundant genogroups.

CrAssphage (cross-assembly phage) is a recently identified bacteriophage which infects *Bacteroides intestinalis*. Several qPCR assays have been developed for quantitative detection of crAssphage, which demonstrated high abundance of this bacteriophage in human feces and sewage. Therefore, crAssphage is currently proposed as a suitable indicator of human fecal contamination of aquatic environments (Stachler et al., 2017; García-Aljaro et al., 2017; Ahmed W. et al., 2019; Ballesté et al., 2019; Wu et al., 2020).

Other viral indicators

Pepper mild mottle virus (PMMoV), a plant virus which infects pepper species (*Capsicum* spp.), is also considered one of the novel human fecal contamination indicators, because of its extremely high abundance in human feces and sewage (Kitajima et al., 2018; Symonds et al., 2018). CrAssphage and PMMoV are successfully integrated in a model, QMRAswim, to estimate the risk of illness to swimmers in a recreational water contaminated with untreated sewage (Crank et al., 2019). It has been reported that PMMoV is suitable as a surrogate for assessing disinfection and removal efficiency of human enteric viruses in drinking water treatment processes (Kato et al., 2018; Shirasaki et al., 2018; Shirasaki et al., 2020). Although both of them have a great potential as a human fecal contamination indicator, further studies need to be conducted, especially to confirm the specific abundance of these recently proposed indicators in human feces and sewage, by testing more samples from non-human sources and non-fecally contaminated water.

Continuing challenges

Public health metagenomic surveillance

Public health metagenomics surveillance is new concept of increasing interest. It is one of the main challenges of the coming years to make NGS technologies accessible also to facilities for practical application in the water sector. In addition, for water quality monitoring purposes, standardisation of protocols and long-term sequence data collection and management will be crucial in establishing databases that are important for data comparison and comparative metagenomics studies. Using a combination of NGS approaches in systematic studies of water microbiomes a wealth of information will be produced crucial in water quality assessment and management (Tan et al., 2015).

The next frontier in the genome sequencing application is long-read sequencing, also known as third-generation sequencing (TGS). The recently developed nanopore sequencing technology (Oxford Nanopore Technologies Ltd., Oxford, UK) offers important advantages over other sequencing platforms because can generate long reads that may be exported in real time, and the nanopore-based sequencer MinION^{TM} is a pocket-sized device which is deployable under field conditions (Ji et al., 2020). The applicability of MinIon for metagenomics in complex water samples still needs to be demonstrated.

Unfortunately, the cost of NGS and metagenomics analysis is still high when high level of sensitivity is needed, and the scientific community must still work for improving technological tools, protocols and bioinformatic pipelines for the sensitive and quick identification of low concentrated pathogens in complex matrices such as superficial water and urban sewage.

Antimicrobial resistance in the water environment

The evidence associated with antimicrobial resistance (AMR) in the water environment and the human health impacts and how to manage these risks are still in its infancy. Globally, there are more questions than answers currently on the topic of wastewater treatment and the removal of antibiotic resistance genes or the flow of such resistance genes into the environment and what it implies for nature but more specifically to the burden of disease and human health. Our group therefore recently saw the need and launched a special issue call on AMR in water environment in Journal of Water and Health, IWA Publishing. Once enough evidence of human health impacts is available, guidelines for the safe use and reuse of water for the management of resistance genes will be developed.

Wastewater reclamation and reuse

There is an increasing need to recycle or reuse and the direct re-use of wastewater for potable water or the increasing reuse of water for different purposes, has various implications from a health-related water microbiology perspective. Direct treatment and reuse of wastewater for potable water and the recycling or reuse of wastewater or beneficiation and by-products of for example algae to remove nutrients from wastewater effluent, and the reuse of such byproducts for fertilising crops, is another water and health interface where our group will be involved.

Culture-independent assays for the infectivity of human enteric viruses

Viral genetic materials are detected by gene amplification techniques even at very low concentration, but we cannot distinguish viable viruses from inactivated ones with molecular detection methods. The low concentration of enteric viruses in environmental water samples does not allow us to use culture-dependent assays for detecting viable viruses, because their detection limit values of culture-dependent assays are commonly too high. However, our main interest is to assess human health risks posed by viable microbes in water, which has encouraged HRWM SG members to develop culture-independent assays. Recent studies are often using capsid integrity quantitative PCR (qPCR) assay using intercalator reagents, such as propidium monoazide (PMA), for distinguishing genetic materials of viable virions from those of inactivated ones (Leifels et al., 2021). The capsid integrity qPCR has been applied to viruses in surface water, tap water (Canh et al., 2021), and wastewater (Canh et al., 2021), and also the evaluation of inactivation efficiency (Loeb et al., 2021). Further application of this culture-independent assays is expected to investigate the potentially infectious viruses in water.

Wastewater epidemiology

Currently, many HRWM SG colleagues are devoted to the sewage surveillance of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which is causing a devastating outbreak of the novel coronavirus disease 2019 (COVID-19) all over the world. Since genomic RNA of SARS-CoV-2 is excreted with feces of infected persons, sewage surveillance has a great potential to provide valuable information of SARS-CoV-2 trends in sewersheds, as mirror of the increases or decreases in the circulation of COVID-19 in the population (Ahmed et al., 2020; Kitajima et al., 2020; Lodder and de Roda Husman, 2020). Prof. Joan Rose, a former HRWM chair and a member of HRWM Advisory board, is chairing the COVID-19 task force of IWA and leading global efforts to monitor SARS-CoV-2 in sewage. These activities of HRWM SG members can provide support to make the difficult and complex political decisions on the imposition or termination of a curfew in the COVID-19 world. In the pandemic response, the knowledge of the HRWM SG on viruses in water, removal by water treatment, and detection methods that the group members have collated over the decades of HRWM's existence, is a very relevant evidence-base for underpinning the virus-safety of water systems.

Disaster water microbiology

Extreme events, including earthquakes, floods, hurricanes, volcanic eruption, happen very frequently on this globe, and at every event a lot of people suffer from public health problems because of lack of clean water and sanitation facilities. HRWM SG has a group so that we discuss possible ideas/methods/responses to any disaster around the world and to have modules that can be easily implemented anywhere. The collective knowledge and experience of the HRWM SG members (with those in other SGSs) should be able to come up with practical resources/modules adaptable to different disaster scenarios. Drinking water production, food preservation, waste disposal, fly/mosquito, injury, heat disorder, and radio-active substance issue at affected areas may be included, but not limited to these and local situations must be taken into account. Our plan is to hold discussions with other SD's to identify who should collaborate with and then form an action plan in the HRWM/WHO workshop at the next SG symposium.

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| 2.8 |

Trends in metals and related substances in drinking water

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Introduction

The IWA Specialist Group on Metals and Related Substances in Drinking Water (IWA-METRELS) is a community of more than 1,000 specialists from around the world with collective focus to stimulate, develop and utilise control strategies for metals and metal complexes in drinking water supplies. The group deals with issues including treating drinking water for removal of inorganics such as iron, manganese, aluminium, arsenic, nickel and chromium, softening and conditioning of water, management of municipal and household water distribution systems with respect to accumulation of metal based solids and leaching of substances such as lead. Geochemical investigations for effectively predicting the long term fate of metals in groundwater aquifers and development of mitigation strategies are also covered by this international group.

Recent developments and trends

Mounting evidence of toxicity of metals and metalloids at low concentrations

In the last few years, a renewed interest has grown towards re-evaluation of the standards and guideline values of metals in drinking water. The primary driver is the availability of new evidence about human health risks due to extremely low concentrations of many inorganic substances in drinking water. For example, arsenic, a naturally occurring metalloid in groundwater which is known to cause cancer in humans, has a maximum allowable concentration of 10 µg/L in most countries around the world in-agreement with the WHO guideline. However, recent studies suggest that As can cause considerable damage to human health even at concentrations lower than the WHO guideline (Kozisek, 2017; Schmidt at al., 2014; Ahmad and Bhattacharya, 2019; Saint-Jacques et al., 2018). Consequently, several drinking water companies in the Netherlands, Denmark and USA are making efforts to reduce arsenic concentrations in drinking water to very low concentrations (Ahmad et al., 2020; Van der Wens et al., 2016). In the Netherlands, the public water companies are determined to reduce arsenic concentrations to below 1 µg/L in the next few years.

Another important example is hexavalent chromium in drinking water. Concerns are being raised in countries such as USA, Germany and the Netherlands for limits of hexavalent chromium, another common carcinogen, in drinking water. Currently the WHO recommends 50 µg/L as the guideline value for total Chromium in drinking water, without distinguishing between trivalent and hexavalent chromium. Chronic intake of hexavalent chromium even in sub-µg/L levels can cause cancer in humans. Therefore, more stringent guideline for chromium are being considered by USEPA and German health authorities.

Mounting evidence of endocrine disrupting properties of metals and metalloids

Cadmium, lead, and mercury are three metals amongst 48 chemicals that has been classified as endocrine disrupting chemicals by the Centers for Disease Control and Prevention (CDC) (Keith, 1997). Arsenic, cadmium, mercury, lead, chromium VI, and uranium have been thoroughly investigated for their impact on the reproductive systems of mammals (Dyer, 2007). Table 2.3 shows a summary of the developmental toxicity, immunotoxicity and neurotoxicity of these metals (Choi, 2004; Dangleben, 2013; Mochizuk, 2019; Wise, 2022; Li, 2018; ATSDR, 2012).

Metals have various endocrine-modulating activities. Arsenic was found to exhibit estrogenic activity, cadmium interfered with the ovarian steroidogenesis in rats, while lead alters the number and affinity of estradiol receptors in rats. Chromium VI has been linked in premature abortion and infertility in females, while sperm health in males is also impacted (ATSDR, 2012). Mercury induces a high rate of progesterone synthesis, which is accompanied by a low rate of conversion to 17-betaestradiol in the oocytes of fish (Choi, 2004). Cadmium, lead and mercury have been shown to produce adverse thyroid hormonal effects. Research on Endocrine disrupting chemicals

Table 2.3 Selected metals and their toxicity

METAL	DEVELOPMENTAL TOXICITY	IMMUNOTOXICITY	NEUROTOXICITY
Arsenic	+	+	+
Cadmium	+	+	+
Lead	+	+	E
Mercury	+	+	+
Chromium (+VI)	+	+	+
(+) Positive / (-) Negative / (NA) Not available / (E) Equivocally			

are still in its infancy and the synergistic and antagonistic impacts of some metals and other chemicals makes it very difficult to pinpoint the hazard. Dose response information is not yet available and further complicates the risk assessment process.

Role of digitalisation in management of metals in groundwater

Digital technologies are playing an increasingly important role in groundwater management from both quality and quantity perspectives. One example where experts of the IWA-METRELS have directly contributed is development of ASMITAS, which is an interactive platform for assessing arsenic risk in groundwater aquifers (Sharma, 2018). The genesis of ASMITAS tool is based on SASMIT research (Hossain, 2014; Hossain, 2017; Ahmad, 2017; Hossain, 2012) with the development of the Sediment Color Tool done by KTH, Sweden and color perception of local drillers for installing safer tube wells (Hossain, 2014). ASMITAS helps to identify appropriate sources of underground drinking water and hence minimise the need for water treatment (Hossain, 2012).

ASMITAS uses advanced color sensor and AI methodologies for color measurements, Munsell color estimations & arsenic risk assessment and it is offered in Edge-Cloud hybrid methodology for fast computing and scaling up the application. ASMITAS offers unlimited potential for providing real time intelligence about the arsenic risk of various water points through Geo spatial mapping, borelogs for understanding the geological structure of sediments and its color & texture characterisation and Arsenic risk profiling through SASMIT protocol (Hossain, 2014; Hossain, 2017; Ahmad, 2017; Hossain, 2012).

Future trends affecting the water sector

New trends in the sector include impact of climate change and water scarcity, willingness to reduce chemical use in water treatment and aging municipal water and wastewater infrastructure. These trends are attracting significant investments in water and wastewater sectors.

One of the ongoing challenges with regards to metals and related substances in drinking water is the high cost of removal of metals and the need for high tech technologies to remove metals from drinking water. This is especially problematic in developing countries. In many developing regions of the world, people are dependent on borehole water which is seldom tested for metals and related substances and therefore people are very vulnerable to exposure. Bioaccumulation of metals through exposure either via drinking water or through the food chain is an important concern and needs immediate attention. Many health impacts have been linked with metal bioaccumulation recently. Therefore, there is a need to develop low-cost water quality monitoring technologies, as well as low-cost water treatment methods. One potential solution to develop low-cost water treatment methods is to use locally available mineral or plant based materials for contaminants adsorption from water.

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| 2.9 |

Tastes, odours and algal toxins in drinking water resources and aquaculture

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Introduction

Globally, taste, odour, and appearance are the key characteristics that consumers apply to judge the quality and safety of water and aquaculture products. Drinking water professionals are increasingly focused on improving consumer satisfaction through advancing capabilities to detect and treat tastants, odorants, algal/cyanobacteria cells and toxins, as well as understanding sensory perception by consumers. Our SG is focused on interdisciplinary efforts that combine the chemical, biological and social sciences with applied engineering for improving the quality of source water, drinking water, and aquaculture products. This report focuses on key recent developments in tastes and odours (T&O) and algal toxins, then portends how the global phenomenon of increased freshwater salinity may affect water quality.

The taste of minerals in drinking water

For consumers, mineral content, as measured by total dissolved solids (TDS), is the major determinant of the taste of drinking water. TDS is associated with people liking their drinking water. Most people find the taste of distilled water flat and undesirable (Dietrich and Burlingame 2015; Dietrich and Devesa, 2019). The amount of TDS that affects liking varies between individuals and populations; a general range is 100–350 mg/L TDS.

Membrane treatment technologies desalinate water with the goal of providing a TDS level that consumers find palatable. Recent research demonstrated that consumers tend to be able to taste a difference in palatability when the change in TDS is about 150 mg/L (Devesa and Dietrich, 2018). Thus, it is important to develop a perspective that consumers evaluate changes in their drinking water relative to their typical drinking water quality and that a “likeable” or “acceptable” TDS level will vary. While overall TDS is the major determinant of taste, the specific ions can contribute favourably or unfavourably to taste as summarised in Table 2.4.

Odour occurrence and challenge for drinking water

Globally, identification and control of odourous chemicals have long been major issues for securing drinking water quality and safety. Recently, China conducted a national odourant investigation at 111 drinking water treatment plants across the country. The results revealed that odour problems occurred widely in source water (> 80%), characterised by earthy/musty (41%) and swampy/septic (36%) odours (Sun et al., 2014). Source water from rivers exhibited more anthropogenic-origin odours (e.g., swampy/septic odour), while that from lakes and reservoirs exhibited more algae-origin odours (e.g. earthy/musty odours). The occurrence of 100 aesthetic events in 140 drinking water treatment plants in 32 cities was further investigated from 2015 to 2018. Of those, 87 odourous compounds were detected in the raw water and 85 in finished water with concentrations that ranged from neutral density to hundreds or thousands of ng/L. Twenty-two chemicals in raw water and 15 in finished water were detected with > 50% frequency. 2-MIB was identified as the main musty/earthy odour-causing chemical in China. 2-MIB had raw water concentrations in the range of n.d.–251 ng/L and detection frequency of 53.8%; in finished drinking water the range was n.d.–576 ng/L with 35.4% detection frequency. Thioethers, including dimethyl trisulphide (n.d.–84.38 ng/L) and dimethyl disulphide (n.d.–714 ng/L), were identified as the major chemical contributors to swampy/septic odour in source water (Wang et al., 2019). Distributions of sulphides exhibited a marked regional effect with higher concentrations being detected in the east and south parts of China. Other odourants, e.g., pyrazines, indoles, dioxanes, dioxolanes, and benzene-containing compounds, were also detected though in low ng /L concentrations.

The Huangpu River near Shanghai has historically possessed complex odour problems involving swampy/septic, fishy and chemical/solvent odours. 2-MIB, geosmin, dimethyl disulphide, diethyl disulphide, and bis(2-chloro-1-methylethyl)ether are usually identified as typical odour-causing compounds (Guo et al., 2016; Guo et al., 2019). Further studies revealed that

Table 2.4 General guidance for specific aqueous ions and their impact on taste of drinking water

ION	GENERAL EFFECT ON TASTE [1]	COMMENT
Na^+	Unfavourable	Too much Na^+ causes poor tasting salty water.
K^+	Neutral	K^+ has low importance for taste and is generally at low mg/L concentrations in water.
Ca^{2+}	Favourable	Ca^{2+} can be optimised to make water taste good.
Mg^{2+}	Neutral to unfavourable	Owing to its typically low mg/L concentrations in natural waters, Mg^{2+} has less importance than Ca^{2+} for good taste. High Mg^{2+} concentrations can impart a bitter taste.
Cl^-	Unfavourable	Too much Cl^- can cause poor tasting water.
SO_4^{2-}	Favourable	SO_4^{2-} has a positive effect on good taste in moderate concentrations.
HCO_3^-	Favourable	HCO_3 should be optimised to make water taste good.
CO_3^{2-}	Unfavourable	Too much CO_3^{2-} causes poor tasting water. Maintaining pH 7 to 8.5 will form HCO_3^- and improve taste.
NO_3^-	Neutral	NO_3^- has low importance for taste and is generally at low mg/L concentrations in water.

Refs: López et al., 2017; Marcussen et al., 2012; Platikanov et al., 2013 and 2017; Vingerhoeds et al., 2016

Table 2.5 Significant recent taste-and-odour events worldwide

COMPOUND	DESCRIPTOR	PLACE	REFERENCES
Dioxanes and dioxolanes	Solvent, chemical	Llobregat River, Spain	Carrera et al., 2019
4-MCMH	Licorice	Virginia, USA	Gallagher et al., 2015
Geosmin and MIB	Earthy/ musty	Worldwide	Watson and Jüttner, 2019 Devi et al., 2021
3-Fluoromethylphenol	Sweet solvent	Barcelona, Spain	Quintana et al., 2019
Bis(2 chloroisopropyl) ether, methyl sulphides	Septic	Huangpu River, China	Guo et al., 2019

the co-occurrence of some cyclic acetals, particularly including 2,5,5-trimethyl-1,3-dioxane (n.d.–133 ng/L) and 2-ethy-4-methyl-1,3-dioxolane (n.d.–167 ng/L), which might be related to resin industries, and could also be responsible for septic/chemical odour in the Huangpu River source water.

Besides severe taste-and-odour episodes that occurred in China over recent years, other relevant events occurred across the globe, as shown in Table 2.5.

Potential impacts of freshwater salinisation on tastes, odours, and algae

Freshwater salinisation is the acknowledged widespread global phenomenon of increasing specific conductance, total dissolved solids (TDS), cations, and anions in surface and ground waters. Increases of two- to five fold in mg/L chloride occurred in global rivers from 1960–2010 (Kaushal, 2016; Kaushal et al., 2019), and a corresponding increase in cations occurred to maintain electroneutrality. Freshwater salinisation can impact the taste of drinking water and shift the ecological profile of a water body.

Diverse causes of freshwater salinisation occur across the globe. Specific freshwater sources will have their own unique causes that occur singularly or in combination. Hydrological causes are natural or anthropogenic, and include alternations in freshwater water flows, sea water rise, storm surges, saltwater intrusion, land clearance, agricultural irrigation, weathering of infrastructure, and climate change (Herbert et al., 2015). Chemical causes are predominantly anthropogenic and include mining/fracking and associate sub-surface disruption and runoff, agricultural chemicals, deicers and anti-icer salts, industrial discharges, municipal/industrial wastewater discharges, water treatment chemicals, personal care and cleaning agent consumer products, and salts in foods (Anning and Flynn, 2014; Herbert et al., 2015).

Freshwater salinisation presents challenges to providing palatable and safe drinking water. The point at which consumers will detect a change in the mineral taste of their drinking water is not known, but will certainly vary between water sources, type of ions causing salinisation, and consumer groups. Temperate regions that use sodium chloride salts to deice roads often receive complaints of salty tasting water in winter and spring. Dissolved minerals that constitute TDS cannot be controlled with conventional treatment and will demand more costly membrane technologies. Salinisation also changes the ecological environment and thus the diversity of algae, cyanobacteria and phytoplankton (Cañedo-Argüelles et al. 2013), potentially influencing microbial-related odour production in water and aquaculture. Increased salinity is observed to cause leaking of the cyanotoxin microcystin from Microcystis aeruginosa (Rosen et al. 2018). Freshwater salinisation and palatability/safety of drinking water is a global sustainability challenge for the water sector in the 21st century.

Biomolecular monitoring of cyanotoxins and T&O chemical producing cyanobacteria

Conventionally, for the monitoring of source water quality, cyanotoxins and T&O chemical-producing cyanobacteria are quantified using taxonomic identification and cell enumeration with microscopy. Although microscopy can enumerate and identify down to the species level, the method is time- and labour-intensive and requires experienced experts who cannot differentiate cyanotoxin/T&O producers from non-producers. Therefore, newer methods are being applied in the water sector, such as quantification of chlorophyll-a and/or phycocyanin using online fluoroprobes (Zamyadi et al., 2016). The pigment-based fluoroprobe approach provides real-time results for cyanobacterial cell numbers/biovolume and even determination of cyanobacterial and algal groups. However, the methods cannot provide species information for cyanobacteria, and therefore do not give detailed information of toxin- and T&O chemical-producers.

Recently, bio-molecular based methods, such as quantitative polymerase chain reaction (qPCR), have been used to quantitatively determine toxin- and odour-producing cyanobacteria and actinomycetes in lakes, reservoirs, and fishponds (Wang et al., 2015; Chiu et al., 2016, 2017; Lee et al., 2018; Lu et al., 2019). Based on the detection of functional genes for microcytins, cylindrospermopsin, saxitoxin, geosmin, 2-MIB and other metabolites, these methods are demonstrated to quantify toxin and odour-producing cyanobacteria in natural waters in Australia, China (Wang et al., 2015), Japan, South Korea (Lee et al., 2018), the Philippines (Lu et al., 2019), Taiwan (Chiu et al., 2016, 2017) and other countries. The gene abundances have been correlated with the corresponding concentrations of metabolites (cyanotoxins and T&O compounds) (Otten et al., 2015; Chiu et al., 2016, 2017), and the gene quotas – i.e., toxin/odour compound mass per copy of functional gene – were obtained for different combinations of toxin/odour compounds and producing genes (Lu et al., 2019). Based on the functional gene and chemical concentrations for microcystins, cylindrospermopsin, and 2-MIB collected from 30 lakes and reservoirs in Taiwan and the Philippines from 2012 to 2016, Lu et al., (2019) compared the conventional cell-based and the gene-based approaches for the risk estimation and management of cyanobacteria in source water. The gene-based approach was shown to better estimate the occurrence of the studied toxins and 2-MIB in the 30 lakes and reservoirs. The results show that biomolecular-based monitoring methods may serve as an alternative decision-making tool for risk management of cyanotoxins and T&O chemicals in drinking water sources.

Sensory techniques in the aquatic environment: present and future

Sensory analysis has a long tradition in the food and beverage industry, including aquaculture, but its application to the water sector is more recent. Although T&O articles about water quality can be found in the literature from 1950, the proposal of the first drinking water T&O wheel in the mid-1980s can be considered as the birth of the sensory science in water as an established discipline.

Flavour profile analysis (FPA) is the most common and useful descriptive method for waters. A panel of judges determines the organoleptic properties of water samples; the samples are characterise based on the T&O wheel that includes descriptors for odours, tastes, and mouth feelings. Threshold odour number (TON) is based on the preparation of successive dilutions of a water sample until the diluted water is perceived as odourless and presents a "neutral" taste to human judges. TON is the reference method for the majority of regulations because of its simplicity, but its principle and usefulness have been questioned. Other methods used in the water industry include flavour rating analysis (FRA), the total intensity of odour (TIO) and the attribute rating test (ART) (AWWA, 2017; Burlingame et al., 2017; IWA, 2019)

Many general food sensory methods are used in our water sector (Gallagher et al., 2015; Vingerhoeds et al., 2016; Platikanov et al., 2017; Devesa and Dietrich, 2018). Aesthetic techniques (i.e, scoring and ranking tests), are used to evaluate the liking of waters, depending on its mineral concentrations or others factors (temperature, level of disinfectant, organic matter, etc.). Difference tests (i.e, triangle, two-out-of-five, and duo-trio tests), are very useful to anticipate if changes in treatment or sources would be noticed by consumers. Threshold methods are widely used to estimate the concentrations at which tastants and odourants are detected and identified.

Chemometrics (principal component analysis (PCA), partial least squares (PLS)) and advanced data mining techniques, such as classification and regression trees (CART) and random forests, are increasing applied to obtain the maximum information from the huge quantity of data given by sensory studies. A few water sector studies implement chemometrics and data mining, but these techniques could be more widely used (Vingerhoeds et al., 2016; Platikanov et al., 2017).

Future focus topics and challenges

The future challenges continue to bedetection, identification, and quantificationof less than ng/L to mg/L quantities of tastants, odourants, and cyanotoxins, as well as sharing data among researchers and practitioners. Devi et al., (2021) developed a comprehensive open access global cyanobacteria and T&O events database (CyanoGM Explorer). The database can be accessed and updated by the global water sector for origin, geographical distribution, cyanobacterial producers, frequency, and monitoring.

Effective and efficient monitoring of organic odourants continues to be innovative. Comprehensive two-dimensional gas chromatography with time-of-flight mass spectrometry (GC×GC-MS) and gas chromatography-quadrupole time of flight mass spectrometry (GC-Q-TOF/MS) are considered the most powerful analytical tools for the identification of odour-causing compounds. The development of an odourant screening database using gas chromatography-triple quadrupole tandem mass spectrometry (GC-MS/MS) is very promising. Also, the development of on-site analytical tools for multiple odorants are urgently needed, such as olfactory biosensors (electronic noses) with enhanced stability and selectivity.

Organoleptic issues in drinking water can result in enormous social impact and psychological fear regarding water safety. Further study covering behavioural responses, psychological aspects, health effects, and effective communications should be performed.

The co-occurrence of many odourants at low ng/L concentrations, often below their individual odour threshold concentrations, creates challenges for determining the contributions to human odour perception. Combinations of individual odourants can show synergistic or antagonistic effects, allowing co-occurring odourants to possibly trigger a relatively strong odour event for consumers. Therefore, it is important to identify the pollutant source and establish a database to collect the fingerprints of odour-causing compounds to better manage odour events.

Efforts should be directed at implementing newer sensory profiling and consumer techniques that are being used in the food and beverage industry, such as check-all-that-apply (CATA), check-if-apply (CIA), sorting and polarized sensory positioning (PSP), TDS (total dominance of sensations, not to be confused with total dissolved solids), napping tests (nothing to do with mapping). Gathering non-verbal responses and consumer emotions is increasing being used by the food and beverage industry to gain feedback on product acceptability; important methods include Facial Expression Analysis and Pupillometry. Why not in the water sector too?

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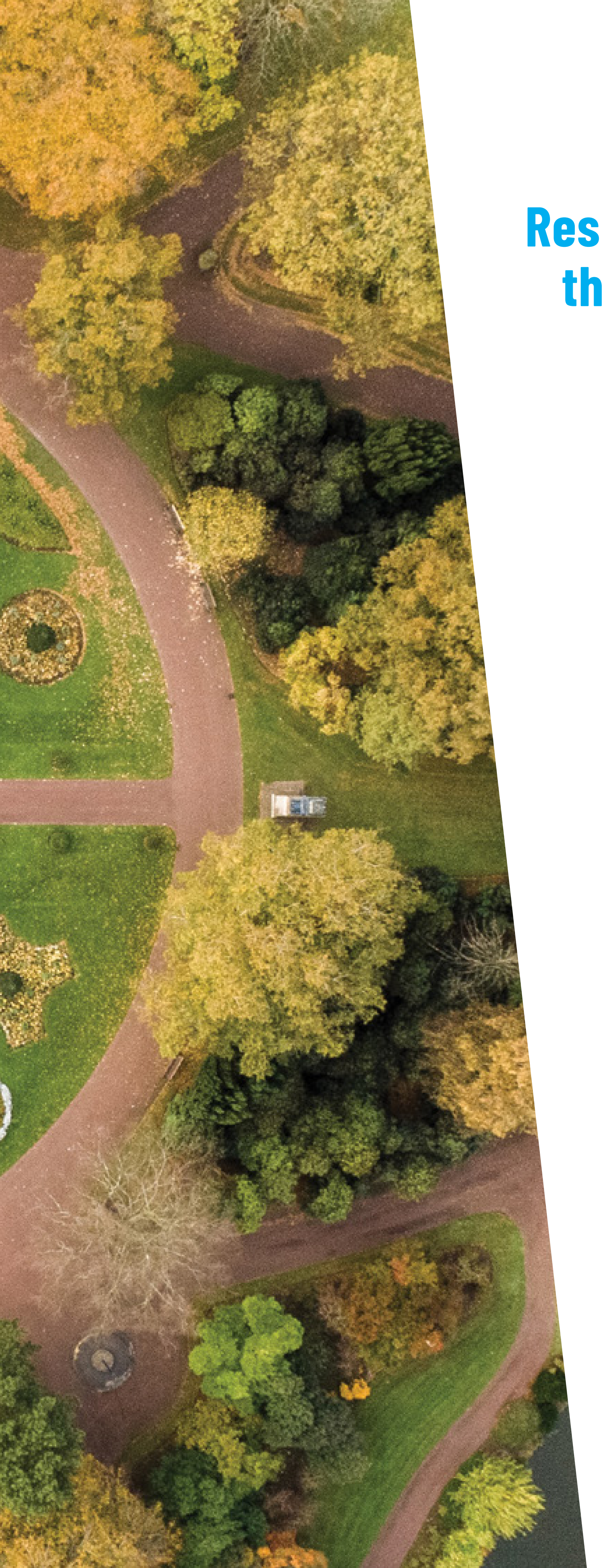


| 3 |

Resource recovery and the circular economy

Reviewed by Fabiana Tessele
and Professor Ana Soares

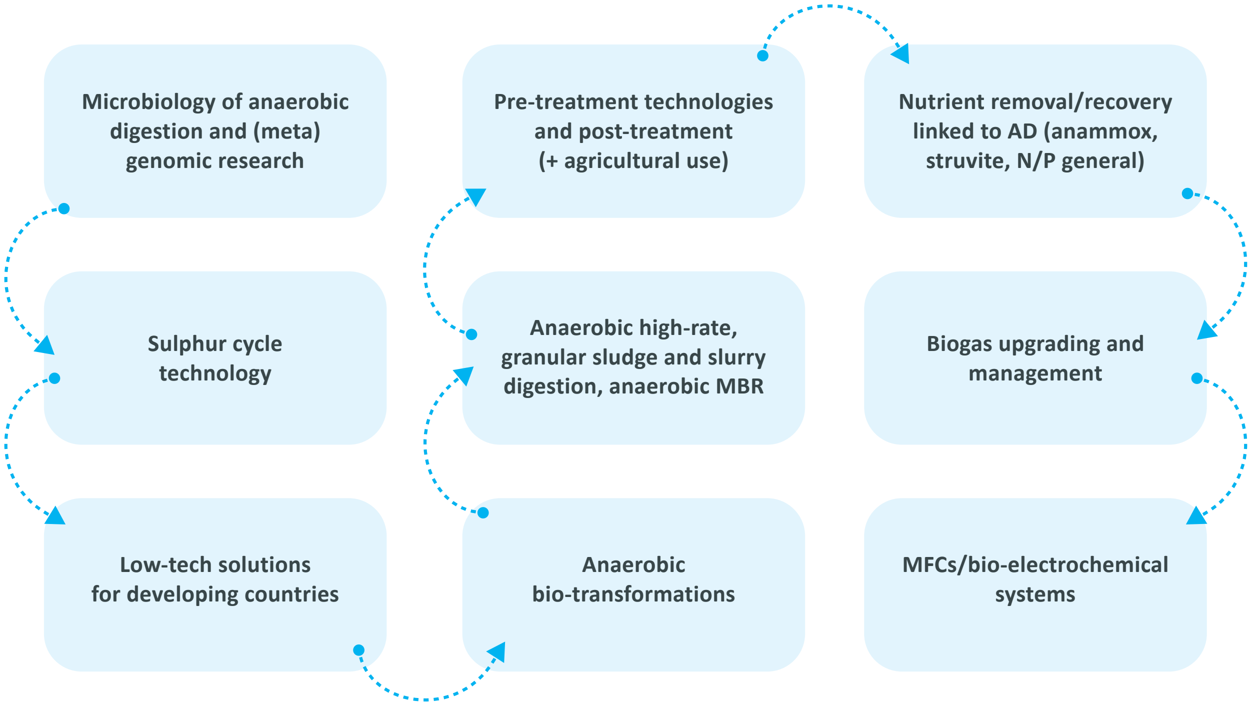
| 3.1 |

Anaerobic digestion

Authors: *F. Tessele and J. B van Lier, on behalf of the Anaerobic Digestion Specialist Group.*

Introduction

The Anaerobic Digestion SG is one of the most active IWA Specialists Groups, with over 2400 members, active coordination of three task groups or working groups, and organisation of on average, one Specialist Group conference per year. The success of the Group is highlighted by the success of our recent World Conference – AD16 in Delft (NL). The conference was attended by about 750 delegates coming from 51 countries. The theme of the 16th issue of the Anaerobic digestion (AD) conference series was “Accelerating natural cycles with anaerobic digestion”. AD makes use of natural conversion processes contained in an engineered environment. As such, AD accelerates natural cycles from small to large scale using a wide variety of substrates such as organically polluted industrial wastewaters (van Lier et al., 2015), municipal/domestic sewage (Chernicharo et al., 2019), excess sludges, manure and agro-wastes. The application of AD in the industrial setting contributes to the recovery of (biochemical) energy and other resources, including carbon and nutrients. AD16 has further strengthened this evolution, by bringing together and activating the debate across the multiple disciplines needed to understand the processes related to anaerobic digestion. The conference was attended by engineers, biotechnologists, microbiologists, chemists, physicists, mathematical modellers, and technology innovators to participate and critically discuss state-of-the-art of anaerobic digestion and learn about new developments. The main themes that emerged from the conference are shown in the diagram below:



The goal of this review is to further outline challenges and opportunities for supporting a more Circular Economy, including resource recovery, wastes treatment, targeting researchers and practitioners in these areas, as well as promoting and encouraging a wider role for anaerobic digestion technologies in a more diverse range of applications.

Major emerging themes in anaerobic digestion

Perhaps the main *paradigm shift* happening in the past few years concerning anaerobic digestion is that the technology is no longer seen as a "waste treatment" technology, but it is a fundamental enabler of the envisaged "circular economy" through resource recovery, including a.o. energy, safe water and nutrients, from valuable by-products coming from industries, municipalities and agro-industrial settings. In this context, some of the highlights developed in the AD field in the last years included the development of microbial ecology for resource recovery with anaerobic digestion (van Loosdrecht, 2019) and solid-state anaerobic digestion of mixed organic waste (Nigel et al., 2019). Also, another innovative and promising development area is the production of non-animal protein and hydrogen using AD as a core process, helping to simultaneously address sustainability and aspects of food security (Verstraete, 2019). On the environmental protection arena, we have achieved considerable progress on the potential for biodegradation of microplastics in thermophilic anaerobic digesters (Nielsen et al., 2019) and the improved degradation of pharmaceutical compounds (Martins et al., 2018), both themes of concern when it comes to safe water reuse. Considering the variety of applications covered by anaerobic digestion, there are several doors of research opportunities, followed by field application, and the unfolding from these efforts will ultimately impact a higher level of sustainability across industries.

Circular economy and resource recovery via anaerobic processes

Biogas can be considered a central pillar of resource recovery and circular economy. Biogas is an energy carrier and can be stored, potentially serving as a battery. Also, biogas can be produced in many ways and from many different substrates, with different targets in gas quality. In addition, the contribution of biogas production to GHG emission reduction can be significant, provided biogas does not escape to the atmosphere. In municipal wastewater treatment, AD processes play a crucial role in attaining energy neutrality in these systems, requiring further insight into the excess sludge conversion potential (Gonzalez et al., 2018).

AD applications combine the production of renewable energy with the stabilisation/mineralisation of organic waste, production of biofertilisers, minimisation of greenhouse gas emissions in agriculture, and the energy-efficient protection of surface water, groundwaters, and aquifers. The multifunctionality of the AD concept is its clearest strength. Sustainable biogas systems include processes for the treatment of residual streams (waste), for the protection of our environment, for the conversion of low-value material to higher-value material, for the production of electricity, heat and/or advanced gaseous biofuel. (Fagerström et al., 2018)

AD also contributes to improved nutrient uptake efficiency in agriculture, by replacing synthetic, fossil fuel-based, fertilisers with biofertiliser products. Biogas can contribute to decentralised energy security, through a transition to a bio-based renewable energy production system, better balancing the localised energy supply (Pabón-Pereira et al., 2019). AD sustainably contributes to the process organic waste streams across the entire food supply chain. What previously was considered to be waste and liability is instead included in a production cycle where organic material and nutrients are returned to the soil to replace chemical fertilisers.

In an increasing number of AD applications, the produced biogas is upgraded to biogenic methane for vehicle fuel or as a natural gas substitute in gas-grid systems. Therefore, AD can be considered as a means to connect decentralised biomass production to a (de)centralised gas grid. An alternative scenario is pictured by Verbeeck et al. (2018), where biogas is upgraded to biomethane, injected into the existing gas grid, and used elsewhere to produce syngas. The H_2 / CO mixture is then used as feedstock for the synthesis of platform chemicals and fuels. This approach could promote AD as an important driver for a future bio-based economy.

In most cases of biogas upgrading, the CO_2 is separated from the CH_4 using different types of techniques, whereafter the CO_2 is also reused for different purposes. The company Solar Foods, from Finland, is in the late stages of developing a revolutionary source of proteins, using fermentation, renewable energy and biogenic CO_2 for instance (Vainikka, 2019). Other applications use H_2 (produced by wind energy) to reduce the biogas CO_2 to CH_4 (Angelidaki et al., Denmark) or apply increased pressures for *in situ* biogas upgrading (Lindeboom et al., 2016).

Microbial electrochemical technologies (METs)

Microbial electrochemical technologies (METs) such as microbial fuel cells (MFCs) are emerging as a promising future technology for a wide range of applications in addition to sustainable electricity generation for decentralised usage. Electroactive (EA) biofilms produced by microorganisms are the key players in the bioelectrochemical systems involving microorganism mediated electrocatalytic reactions. Therefore, genetically modifying the organism for increased production of EA biofilms and improving the extra electron transfer (EET) mechanisms may contribute to increasing the current density of an MFC. At the current state of the art, MFCs are not (yet?) competitive for wastewater treatment but MFC research indicates interesting possibilities for product formation at the cathode side. Indeed, making products at the cathode side could be of interest, although a solar cell could then also be a cheap alternative.

Recent research shows that extracellular polysaccharides (EPS) produced by the organisms, attribute to both biofilm formation and electron transfer (Angelaalincy, 2018). The integration of AD embedded in a microbial electrolysis cell (MEC) with an electromethanogenic biocathode results in increased stability and robustness of the AD process against organic and nitrogen overloads; improved effluent quality and the recovery of ammonium, while at the same time the biogas is upgraded (Cerrillo et al., 2018).

Recent advances in microbial biotechnologies aim at converting waste materials into bioenergy and biomaterials, thus contributing to a reduction in economic dependence on fossil fuels. To valorise biomass, organic materials can be used to produce biopolymers, through different microbial processes. Different bacterial strains can synthesise biopolymers to convert waste materials into valuable intracellular and extracellular bioproducts, which are useful for the production of 'green' biochemicals (Pagliano et al., 2017). Therefore, the development of high-performance microbial strains and the use of by-products and waste as substrates could reasonably make the production costs of 'green' biodegradable polymers comparable to those of petrochemical-derived origin. This brings along the potential of creating a unique integrated system because it represents a new approach for simultaneously producing energy and biopolymers e.g., the plastic industry, using by-products and waste as organic carbon sources.

During reductive stabilisation of organic materials, no oxygen/energy is required, whereas the biochemical energy is contained in the end-product. The classical biogas end-product is CH_4 but many researchers point at possibilities to stop earlier in the process, e.g., producing VFA for the carboxylic acid platform. Local conditions will determine which is most sustainable in that specific location.

Bioprocessing and bioproduction

AD has to be considered in the context of the current mindsets dealing with energy, climate change and also the need for more sustainable production of chemicals and even proteins (Verstraete, 2019). Incremental improvements in the AD technology must be complemented by a set of quantum leaps, such as (a) harvesting the solar energy by using the inherent methanogenic capacity of deep soils; (b) integrating decentralised biogas production in centralised bio-based petrochemistry and (c) choosing radically for cleantech by combining AD with the production of clean gases, which are subsequently aerobically fermented to microbial protein. Clearly it needs to become part of multivariant value chain, and it should particularly demonstrate its potential to contribute to the transformation into a more sustainable society.

In recent years the goal is no longer to destroy reactive nitrogen but to develop technologies to incorporate low value mineral nitrogen into protein-rich microbial biomass. The incorporation of nitrogen into microbial protein can be driven by various mechanisms such as providing organic carbon and electron donors like hydrogen and carbon monoxide. Hydrogenotrophic microbial growth, for instance, delivers multiple benefits by incorporating ammonium, carbon dioxide, hydrogen and oxygen, thereby not only fixing carbon dioxide but also converting ammonium into valuable, protein-rich biomass in an efficient and sustainable way. This new concept up-cycles reactive nitrogen and transforms what was considered waste into valuable products such as human food, animal feed, and organic slow-release fertiliser. The market potential for these valorisation chains are under exploration, but there is no doubt that there are substantial, future opportunities.

As a concrete example, the Finish entrepreneur and researcher Pasi Vainikka founded Solar Foods, representing an alternative approach: one that promises to facilitate large scale but sustainable food production of a non-animal protein (Solein) by reducing the planet's dependence on land-intensive livestock farming. The process by which Solein is produced not only requires a small fraction of the land required to produce a similar amount of beef – the modest amounts of water used can be cleaned thoroughly before being released back into the environment. (Vainikka, 2019).

Advanced wastewater treatment

At present, the removal of organic micropollutants (OMPs) is one of the biggest challenges in advanced wastewater treatment, especially where direct potable reuse is being considered as part of the water supply matrix. Biotransformation of OMPs in wastewater treatment plants ultimately depends on the enzymatic activities developed in each biological process. Recent studies have investigated the enzymatic transformation of OMPs under anaerobic conditions (Gonzalez-Gil et al. 2019). These studies are unravelling biotransformation of OMPs in wastewater treatment systems, allowing for developments in the field.

Microplastics have emerged as new environmental pollutants. Biodegradation of polypropylene under thermophilic conditions was observed to be several orders higher than in any other environment investigated previously (Nielsen et al., 2019). The findings have shown a high potential for biodegradation of microplastics in conventional AD reactors. The results furthermore support the use of applying anaerobic digesters for the treatment of highly energetic household waste with a high content of plastics. Biological systems aim for the highest level of efficiency to recover a maximum amount of energy, while wasting only a negligible amount of resources. Anaerobic digestion is a well-established technology for the recovery of organic carbon in the form of biogas. This is however a low value application. Recovery of organic compounds as chemicals has a higher rank with respect to sustainability and circular economy. Chemicals have often a higher value, which can make the recovery more interesting. In this respect the methanogenic fermentations should be halted at the level of fatty acids or alcohols from where more higher value products can be derived, whenever this is economically feasible (van Loosdrecht, 2019). This means that the ecology of fermentation processes should be better understood. The traditional approach is evaluating the microbiome and selecting the right microorganisms. Contrary it might be more worthwhile to select for the right metabiome. This would need to think on what selects for a certain conversion instead of a certain microorganism. Several excellent researches that try to unravel the microbiome of digesters. It's incredible what has been unveiled in the past decade.

Conclusions and research & development agenda

Considering the variety of applications covered by anaerobic digestion, there are several doors of research opportunities, followed by field application, and the unfolding from these efforts will ultimately impact on a higher level of sustainability across industries. The new AD developments give ample possibilities for new business that strive to implement these technologies into practice.

Anaerobic digestion has secured its place as the central pillar of resource recovery and circular economy. Biogas is an energy carrier and can be stored, potentially serving as a battery. In municipal wastewater treatment AD processes play a crucial role for attaining energy neutrality in these systems, requiring further insight in the excess sludge conversion potential. In addition to further processing and value add of the excess sludge (biosolids), control of nitrous emissions and others, and further developing the understanding of ecology of fermentation are areas of focused research. Next to biogas, the reductive formation of chemical building blocks or biopolymers is indeed an emerging field that may position AD more centrally in the envisaged bio-based circular economy.

Beyond the wastewater treatment and energy production, findings have shown a high potential for biodegradation of microplastics and organic micropollutants in conventional AD reactors.

However, while considering circularity we should have a close eye on the practical and economic feasibility, meaning that AD specialist should be aware of the entire value chain. The scientific community needs to focus on developing processes and innovation that have potentials for practice, including technology providers and end-users.

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| 3.2 |

Nutrient removal and recovery: trends and challenges

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Introduction

The recovery and reuse of the nutrients contained in wastewater is highly desirable towards the establishment of a resource-oriented, circular economy. Globally, almost one-fifth of the mined phosphorus is found in human excreta and, in principle, wastewater could provide one third of nitrogen fertiliser requirements (Kehrein et al., 2020). Land application of nutrient-rich biological residues, such as animal manure, dates back to the origin of agriculture. Nowadays, direct spreading of sewage sludge to agricultural fields is common practice yet environmental and health concerns do exist. Also, over the last decades, increasing urbanisation and the intensification of agricultural systems have promoted extensive research on alternative indirect recovery solutions. Yet, while numerous processes and technologies have been developed at laboratory or pilot scale, their industrial implementation remains very limited. Besides technical challenges, the main bottlenecks for their wider adoption reside primarily in the cost of the processes and the market value of the recovered product. A more holistic approach, including societal and market stakeholders beyond the mere technical focus, is required for the paradigm change from wastewater treatment plants (WWTP) to water resource recovery factories (WRRF).

Existing knowledge

Nitrogen, phosphorus and potassium are essential nutrients for agricultural activities, thus their recovery for fertilisation purposes remains the primary focus of research and implementation endeavors. Even though technical solutions for N and P recovery are available, most of them are economically marginal due to the current low cost of commodity fertilisers. Consequently, there is a need to identify opportunities for nutrient recovery products in a wide range of industrial sectors beyond agriculture or the fertiliser market to provide stronger economic drivers for a circular (closed-loop recovery and reuse) approach to nutrient management (Kehrein et al., 2020).

The current state-of-the-art approach for P recovery first entails a bio-concentration step in enhanced biological phosphorus removal (EBPR) processes as a means to partition P to a concentrated sidestream. Subsequently, P can be re-solubilised via number of approaches, and finally precipitated as struvite ($MgNH_4PO_4{\cdot}6H_2O$) or brushite ($CaHPO_4{\cdot}2H_2O$) (Egle et al., 2016). Alternative approaches target P recovery after biosolids incineration, for example via wet leaching. While feasible from an economic and resource recovery standpoint (particularly when co-benefits are considered), in general these processes only partially recover P. An increased research focus for P recovery has therefore been to target larger amounts of overall recovery with lower chemical consumption, and to target P recovery at plants (often the larger ones) that rely on highly-efficient chemical rather than biological removal.

In analogy, numerous physical, chemical and, to some extent, biological techniques have been identified for N recovery from concentrated sidestreams (Beckinghausen et al., 2020). Most of those techniques recover nitrogen as ammonium sulfate in the form of crystals or liquid solution (with 5- to 10-fold higher value than struvite), but none of them targets the production of urea which is the most commonly used fertiliser on a global scale. Also, N recovery has been the focus of extensive work in the laboratory, but has seen very little translation to practice primarily due to the high cost and energy expenditure (e.g., ensuring high pH and temperature for effective ammonia stripping). At the same time, the optimisation of process design and operation can lead to major improvements in costs and energy requirements of the recovery, e.g., full heat recovery in vacuum stripping or air recirculation in column stripping. Furthermore, new opportunities may arise from nutrient management in alternative, inherently more concentrated streams ranging from source separated urine, food waste, agriculture and aquaculture and should be given more attention.

It is here also paramount to highlight that nutrient removal and recovery should not necessarily be considered as competing alternatives but rather complementary solutions towards treatment schemes maximising resource efficiency at minimum environmental impacts. Important examples here are resource efficient shortcut N removal processes (e.g., mainstream nitrite shunt or nitritation/anammox), which do not recover N but significantly decrease energy requirements for nutrient management and directly support the goals of energy neutrality and carbon recovery. Moreover, the same processes could in principle be used to polish the effluent of recovery plants guaranteeing their compliance with increasingly stringent discharge limits. In this perspective, integrated nutrient management should therefore take into consideration economic indicators and overall environmental impacts, such as greenhouse gas (especially nitrous oxide) emissions and carbon footprint, development and application of sustainability metrics, energy efficiency, use of recovered products, and chemical usage.

General trends and challenges

The dilute nature of wastewater and the low volumes of recoverable products relative to competing industrial processes and established market demand constitute intrinsic challenges for nutrient recovery. On the one hand, as recovery efficiencies decrease at low concentrations, novel technical approaches aim at combining nutrient accumulation, followed by a subsequent release phase that mobilises the nutrients for their final recovery as concentrated products (Metha et al., 2015). On the other hand, besides potential environmental/health risks and social acceptance of the recovered products, close evaluation of process economics and the development of robust (niche) value chains are foundational for the wide adoption of nutrient recovery solutions (Kehrein et al., 2020). In this perspective, the following challenges are identified for the coming years:

- cost and high energy requirements of technologies;
- complexity of the recovery processes and availability of skilled labor force; low value of nutrient recovery products from wastewater facilities, particularly commodity fertilisers;
- limited recovered materials volumes hinder the study and engineering of application alternatives;
- identification of and synergy between all stakeholders from recovery to product use.

In terms of general trends, the following topics are discussed in the next sections in the framework of nutrient recovery within a more circular economy:

- P recovery integrated with chemical P removal;
- N recovery from concentrated streams;
- biosolids fertilisers for combined P and N recovery;
- uncoupling nitrogen and carbon treatment for improved resources recovery;
- development of cross-sector partnerships to drive recovery.

Nutrient recovery technology trends

P recovery integrated with chemical P removal

During the past decades, a vast number of new technologies have been developed for advanced P recovery from EBPR based sewage sludge and sludge liquor streams as well as from sewage sludge ash (Kehrein et al., 2020). The mature and most accepted phosphorus recovery technologies involve recovery of P in the form of struvite or brushite crystals from biological P removal-based sewage sludge and sludge liquor streams. So far, business cases for such technologies have been challenging and are driven by additional benefits (i.e. decreased maintenance cost resulting from prevented in-pipe scaling) rather than recovery product value itself. Moreover, only about 20–40% of the inlet P is recovered through this approach, while only a limited number of alternative technologies have been developed for P recovery from effluent wastewater characterised by low concentrations and high volumes. These include ion exchange or the use of selective adsorbents. However, the scope of available technologies has been limited to cover future recovery needs in different types of phosphorus streams in the wastewater treatment sector alone.

In parallel, chemical precipitation of phosphorus is a globally used method in phosphorus removal, and it is an essential step when low or extremely low effluent concentrations are required to protect receiving waters. In addition, it is a relatively stable and adjustable process compared to EBPR schemes. However, the potential of chemical precipitation for P recovery was only recently truly appreciated. During the last five years new technologies have been developed targeting chemical P removal plants. Finnish RAVITA from HSY Water Utility (HSY, 2022), and Dutch ViviMag from Wetsus and TU Delft (Wetsus, 2022) are recent examples of new perspective technologies. In case of RAVITA phosphorus is recovered as phosphoric acid and as vivianite in case of ViviMag. The main idea in the RAVITA process is post-precipitation of P from the water phase at the end of the entire wastewater treatment process to produce a separated chemical sludge (Rossi et al., 2018). The separated chemical sludge is then processed further by dissolution and solvent–solvent extraction steps, resulting in phosphoric acid as the main recovery product. Alternatively, the ViviMag technology is based on a magnetic separation process, by which the insoluble iron phosphate mineral vivianite is recovered from sewage sludge after anaerobic digestion (Wetsus, 2020). During anaerobic digestion, Fe(III) is reduced to Fe(II), which results in vivianite formation, and the separation relies on the paramagnetic character of the vivianite mineral. Both technologies are currently being piloted and show high P recovery potential (>70% of inlet P). Future testing and research will need to provide insights into product value, ease of operation and overall business case.

N recovery from concentrated streams

While ample research has targeted the goal of nitrogen recovery as a fertiliser, efforts to date are largely limited to the laboratory with very little adoption in practice. A small number of facilities have implemented ammonia-nitrogen stripping and recovery as salt from concentrated sidestreams (e.g. anaerobic digester centrate), but this approach has in most cases proven not economical. In principle, nitrogen can also be recovered from concentrated sidestreams as struvite (magnesium ammonium phosphate) via mature technologies. However, these approaches are primarily aimed at phosphorus recovery and prevention of nuisance from struvite formation, and leave the majority of reactive nitrogen in wastewater owing to the typically encountered low P:N ratios. One appealing approach to nitrogen recovery is direct use of nutrient laden effluent for irrigation (termed fertigation). This approach has however seen limited implementation due to public health concerns and excessive pumping energy requirements to transport treated effluent from urban to agricultural settings, but may prove more feasible if integrated with nascent urban agriculture efforts.

Because high concentration is considered crucial to cost and energy effective nitrogen recovery, a range of emerging technologies have been proposed to either partition nitrogen from the mainstream to a concentrated sidestream or to prevent dilution in the first place. These approaches include source separation (urine diversion), electrochemical or microbial-electrochemical techniques, adsorption, ion exchange, and membrane separation. This remains a robust area for innovative technology development to allow for energy and cost-effective N partitioning and recovery. Moreover, there is increasing interest in recovering nitrogen not only as a fertiliser but also as a bioenergy source (e.g. ammonia or nitrous oxide), or as other more complex and high value bioproducts. One very promising target is single cell protein, which can then be used as animal and potentially human feed or as a building block for nitrogenous platform chemicals. Most efforts to date have investigated heterotrophic protein production, which functions more for carbon than for nitrogen recovery. Nascent efforts also target chemo or photo-autotrophic and single cell protein production, but these efforts are in early stages.

Biosolids fertilisers for combined P and N recovery

The biosolids resulting from anaerobic digestion are usually rich in N (2%) and P (4%), and represent a low-value and low-cost effective alternative to commercial fertilisers. Their application reduces the demand for commercial petroleum-based fertilisers along with the energy required for their production. Moreover, besides the simultaneous N and P recovery, the high biosolids organic content increases water holding capacity and overall soil structure. Consequently, land application of biosolids remains a great opportunity in regions where land application of manure is limited and where low industrial intake results in minor metal content of biosolids. From a sustainability point of view, using biosolids generated locally will decrease emissions, carbon footprint and costs associated to hauling of this valuable product far from its source. In addition, organic fertilisers can create conditions where the fields can act as a carbon sink instead of carbon releases and could therefore be a strategy for climate change mitigation. Biosolids land application has also been shown to increase plant yields and provide better drought resistance, thus potentially increasing resilience of agriculture sector. In recent years, increased commercialisation of biosolids products (for example, Bloom product in Washington, DC, USA) or development of regional groups (i.e., Carbon Action from Baltic Sea action group) indicate renewed interest in biosolids fertilisers. Within these examples, the collaboration and close communication between utilities, scientists, farmers, gardening communities and others was essential to provide clear information on biosolids quality and to work together for sustainable agriculture.

In the USA, due to federal regulations, biosolids are far more regulated and studied than other soil amendments on the market. Class A biosolids is the preferred quality for land application. Application of biosolids could involve plant establishment, turf establishment, lawn topdressing, topsoil blending, potting soil blends etc. Unfortunately, pharmaceuticals, anti-microbials and other trace organic compounds are persistent and found nearly everywhere in modern society. Many of these chemicals are found in bagged fertiliser products available at garden stores. Biosolids contain these compounds at very low levels too. Continued monitoring and research is needed to better understand impact of trace contaminants in biosolids in relation to the proposed applications.

Uncoupling N and C treatment for improved resource recovery

On-site energy recovery remains the low hanging fruit for resource recovery in wastewater treatment plants yet, at the same time, it is also a major driver for the development of processes and technologies with broader potential applications. Energy recovery requires the (partial) uncoupling of carbon and nitrogen treatment to enhance carbon redirection from wastewater to sludge that is subsequently anaerobically digested with co-substrates (Maktabifard et al., 2020). To this end, novel solutions for nitrogen removal requiring less or no carbon are the subject of intense research.

Energy neutrality or even energy positive wastewater treatment should be feasible, and typically about 60% carbon redirection is sufficient to balance energy needs for treatment. New advances in carbon redirection technologies include high-rate activated sludge systems with enhanced solids retention using biofilms or membranes, high-rate contact stabilisation concepts, and alternating activated adsorption (AAA) processes. Advances in anaerobic digestion focus on intensification of anaerobic digestion systems and increasing biogas yields by pretreatment technologies such as thermal hydrolysis. At the same time, pilot-scale projects are already exploring the recovery of the carbon in the form of higher added-value products, such as bioplastics (e.g. polyhydroxyalkanoates) or commodity chemicals (e.g. medium-chain fatty acids). At the same time, new advances in shortcut nitrogen removal processes such as nitrite shunt process (nitritation/denitritation), deammonification (partial nitritation/anammox, PNA) and partial denitrification combined with anammox (PdNA) strongly reduce both the carbon and energy required for nitrogen removal. In the framework of water resource recovery facilities (WRRF), these processes could be implemented as a resource-efficient polishing step after nitrogen recovery. Anammox-based processes are of particular interest as in principle extremely low effluent concentrations are achievable without recirculation needs.

Development of cross-sector partnerships to drive recovery

Most of the identified bottlenecks that currently hinder the adoption and implementation of nutrient recovery technologies still relate to process economics and value-chain development (Kehrein et al., 2020). In this regard, water management utilities historically possess consolidated know-how on process development and operation, and are thus expected to continue playing a prominent role in future endeavours. However, even if all the challenging open technological bottlenecks are solved, resource recovery is likely to remain a niche activity. Circular economy stimulation requires new and broader ways of thinking and cross sector networking to avoid narrow focus challenges during the innovation process. Typically, product development or business model processes miss some aspects or end users' needs, which can cause time or economical losses or even the rejection of the development. Some potential end user group can be even left out of the scheme. Development of cross-sector partnerships is paramount to avoid or minimise these challenges. Ecosystem thinking is one option for this partnership development. In Finland, a Nutrient recovery business ecosystem has been tested during the years 2016-2019 by the Baltic Sea Action Group (BSAG) and the results were positive. More than 70 cross-sector partners from multiple sectors participated to the ecosystem actions like seminars and workshops. Many of the connections and so-called positive hits are still active even as the official BSAG ecosystem is already closed. In the future, regional water management utilities could also develop a common recovery strategy for selected resources that coordinates efforts to exploit synergies and the advantages of economies of scale. If several utilities recover the same resource, value-chain development could be facilitated by acting as one supplier, thus increasing their collective market power.

Conclusions and research or development agenda

The recovery of the nutrients contained in wastewater is highly desirable in view of a more circular use of resources. Numerous technologies do exist, yet their industrial implementation remains very limited primarily due to demonstrable process economics but also due to the lack of established market value-chains. Development of new nutrient recovery business ecosystems will offer exciting new drivers and opportunities for research and applications.

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| 3.3 |

Particle separation

Authors: *Arjen van Nieuwenhuijzen, Pascal Guiraud, Harsha Ratnaweera, Stefan Panglisch, Mark Wiesner and Katsuki Kimura on behalf of the Particle Separation Specialist Group.*

Introduction

Particle removal nowadays is not only essential to proper water and wastewater treatment, but also offers the possibilities for optimisation of energy efficiency of treatment processes and for energy and nutrient recovery from wastewater and sludge treatment. It should be noted that a large portion (>70%) of organic matter in municipal wastewater is present in suspended and colloidal "particles". Efficient particle separation could therefore have a significant impact on circular economy and resource recovery. Advances are underway in conventional coagulation/sedimentation/filtration, and many types of new technology have been introduced at drinking water treatment plants. These important topics have been intensively discussed in previous specialised Particle Separation conferences.

Resource recovery from wastewater by particle separation processes

Urban municipal sewage is regarded as a resource that contains many valuable materials, such as nitrogen in the form of ammonia, phosphorus as fertiliser acid, organics, cellulose and sand. These valuable components should be separated in an industrial set-up, leaving the individual components as much as possible intact. Contrarily to present wastewater treatment plants where biological processes are applied that destroy and convert the organic components into CO_2, CH_4, N_2O - harmful greenhouse gases, only physical separation and concentration processes are applied in the resource-recovery oriented plants. The organic matter and nutrients remain intact, without emitting green-house gasses, and can be upcycled to raw materials for several (bio-based) value chains. Figure 3.1 shows a schematic representation of the water and resources refinery concept proposed by a Dutch group (Dutch Water Refinery). In this way waste water will be used for the production of high quality water for specific use: urban greening; development of recreation area; industrial process water and agriculture. Also, production/recovery of valuable products such as cellulose (for bio-composite or building material, pulp & paper industries), ammonium (as ammonia sulphate or nitrate for chemical industries), phosphorus (as phosphoric acid for chemical industries), organic biomass (for further up-processing into fatty acids, biopolymers or even bioplastics) and minerals (e.g. potassium for soil improvement on farm land and calcium) will be considered.

Advanced technologies for particle and ion separation are used for this purpose. The system doesn't rely on biological processes, but mainly on electro-chemical conditioning and physical separation. Essential process elements are as follows:

- screening and fine sieves: to recover suspended solids which can/will be converted to cellulose and sand;
- electro coagulation (EC) followed by dissolved air flotation (DAF): to recover phosphate, organic compounds and metals;
- direct nanofiltration: to remove removing divalent ions and 80% of the organic micro-pollutants and pharmaceutical residuals and to maximise recovery of organic matter;
- ion-exchange: to remove the mono valent components; especially ammonium and recover highly concentrated ammonium (options for reuse are for example fertiliser or upcycling to proteins).

A promising option for resource recovery from wastewater: harvesting microalgae

Wastewater treatment using photosynthetic microorganisms can benefit from using microalgae, and have received significant attention. To enhance the efficiency of this option, improving particle separation processes for harvesting

Figure 3.1 Schematic representation of the original rural application of the Water & Resource Refinery.

microalgae is important. The microalgae CO_2 fixation capacity and their ability to generate various valuable bio-sourced products of interest, such as organic compounds for pharmaceuticals and cosmetics, human and livestock nutrition, and maybe in the future for biofuels, give them sustainable interest to reduce the environmental footprint of mankind. Wastewaters, as a cheap source of nutrients and inorganic carbon is promising for the mass production of algae-based commodities. Microalgae based treatment systems may reduce wastewater treatment costs via the recovery of its inherent resources, while providing effective sanitation services. Yet, removing microalgae from waters remains a great and difficult challenge for water treatment. This difficulty comes from the very low microalgae concentration (e.g., less than a few mg/L) and highly negative charges on the surface of microalgae. For microalgae production systems, the dedicated harvesting unit operation is the main limitation encountered by industrials. This crucial step of harvesting and dewatering has been assumed to account for one third of the entire price of microalgal biomass production in industrial processes. Several methods have been proposed for microalgae harvesting, including centrifugation, filtration, flocculation and flotation. However, most of these methods present high costs and energy consumption, often for low efficiency rates. For instance, centrifugation, the most commonly used method for harvesting in microalgae production, consumes a large amount of energy and can cause damages to the cells because of the high shear forces. Filtration involves using membranes, which, in the case of microalgae separation, can get clogged because of the small size of the cells and of the production of exopolymers (EPS) by the cultivated cells, resulting in high operating costs. As for flocculation and flotation, they seem to be promising low-cost approach for large-scale harvesting; however the chemical flocculants used to induce flocculation is a major issue in these techniques and they end up in the harvested biomass, and can interfere with the final application of the biomass (food or feed).

Several challenges for research and technical developments have therefore to be addressed. The first issue is to understand at the microscale the interactions between microalga walls and colloids or interfaces involved in their growing medium and in the separation systems (bubbles, flocs, membranes, filtering particles…). With the help of this better understanding, special efforts can be undertaken to develop and to test nontoxic bio-floculants. Controlling the EPS production by microalgae during growing is another important challenge to apply membrane and filters without oxidation pretreatments. However, self-produced EPS are promising natural floculants for flocculation and flotation separation technologies.

Automation and remote control of particle separation processes

The particle removal processes and approaches once considered as adequate are no longer meeting the increasing treatment and operational requirements: managing emerging contaminants (Kim and Zoh, 2016), high removal of NOM while keeping residual aluminium to a minimum (Zhang et al., 2016), extremely low nutrient discharge limits, ambitions for resource recovery mentioned above are becoming common. The need for more compact, energy and resource efficient plants with increasing automation are now anticipated from all plants irrespective of the size. The result is, more and more particle removal process, must rely on real-time surveillance and control to operate in most efficient conditions, like other advanced processes.

While flow and coagulation pH were often satisfactory to define the coagulant dosage, both the need and potential to include other critical parameters such as particles, NOM, phosphates are now acknowledged (Ratnaweera and Fettig, 2015). Innovative solutions to reach optimal coagulant dosing are not only researched but also seen in full-scale applications.

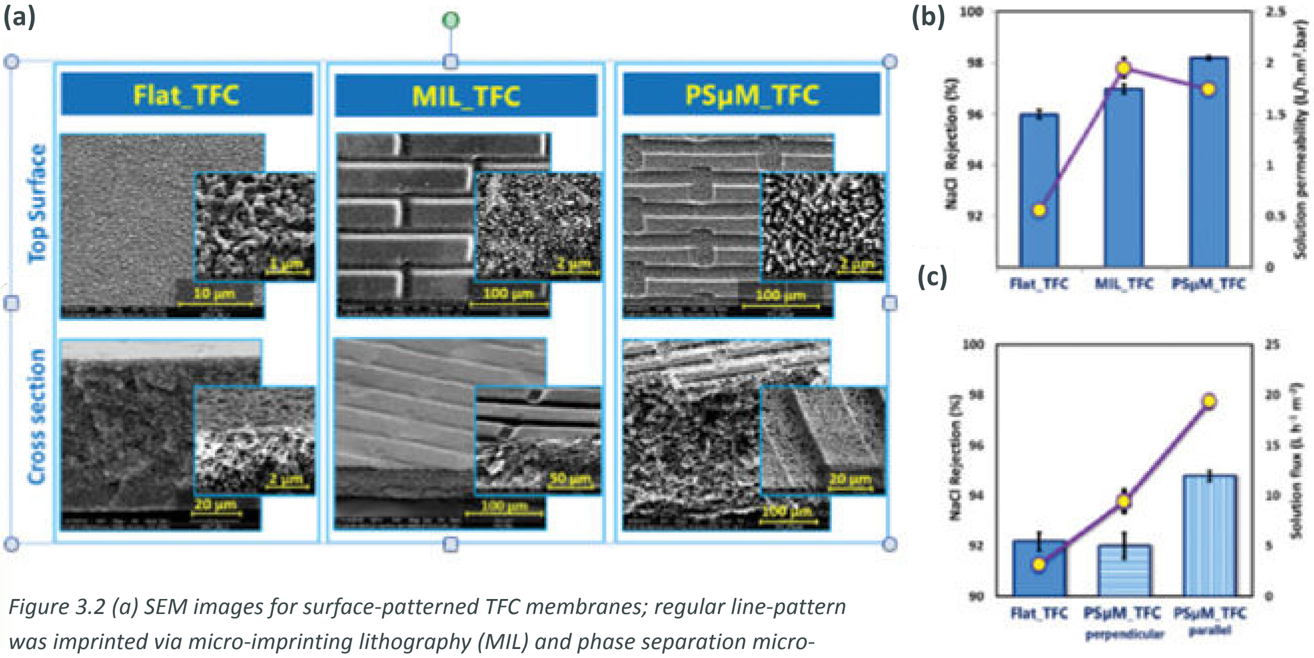

Figure 3.2 (a) SEM images for surface-patterned TFC membranes; regular line-pattern was imprinted via micro-imprinting lithography (MIL) and phase separation micro-molding (PSμM), (b) separation performance using 2,000 ppm NaCl feed at 16 bar, intense stirring and room temperature, (c) influence of surface pattern orientation on separation performance of surface-patterned vs. flat membranes using 10,000 ppm NaCl feed at 20 bar (turbulent flow; Re = 7300), adapted from Choi et al. (2018) and ElSherbiny (2018).

The use of real-time sensors of zeta-potential (Brokett, 2018), virtual sensors (Newhart et al., 2019), image analysis (Sivchenko et al., 2018) either in combination with machine learning and/or artificial intelligence (Yamamura et al., 2020) is in research focus.

While the separation processes become more efficient with the increasing automation and remote process control, they also create concerns related to process safety. Cyber security in treatment plants has been addressed by national and international water organisations, where the real-time surveillance and process control can play a significant role in identifying, preventing and recovering after an attack.

Manipulation of membrane surface

Membrane processes have become important options for particle separation. Surface micro-patterning is recently introduced as promising versatile platform to promote separation performance and antifouling propensity of pressure-driven membranes in water treatment and desalination applications (ElSherbiny et al., 2017; Choi et al., 2018; Malakian and Husson, 2020). Manipulating membranes' surface topography by introducing microstructures, in nano- or micrometer range, have been emphasised to modify fluid characteristics and shear stress on membrane surface toward less foulants / solutes deposition, without significantly increasing pressure drop (Won et al., 2016; Choi et al., 2018). ElSherbiny et al. have developed surface-patterned thin-film composite (TFC) membranes exhibiting superior separation performance and lower tendency for concentration polarisation, compared to conventional flat-sheet membranes, by virtue of enhanced active surface-area and outstandingly promoted surface roughness (Figure 3.2) (ElSherbiny et al., 2017; ElSherbiny et al., 2019a; ElSherbiny et al., 2019b). Furthermore, micro-patterned TFC membranes showed less performance decline in bench-scale dead-end unstirred filtration experiments using silica nanoparticles at constant pressure (ElSherbiny, 2018; ElSherbiny et al., 2019b). This was interestingly interpreted by spatial selective deposition of silica nanoparticles on surface micro-structures, driven by unequal flow distribution, resulting in preferential accumulation of particles in pattern's valleys, while keeping other regions not fouled. A very recent systematic study has emphasised that surface-patterned nanofiltration membranes exhibited 20–25 % higher threshold flux than corresponding flat-sheet membranes in crossflow fouling experiments at constant flux using model silica nanoparticles (Malakian and Husson, 2020). Reliable foulants deposition mechanisms on surface nano-/micro-structures, especially at early filtration periods, have not yet been introduced. The impact of membranes' surface-patterning is revealed to be substantially influenced by foulants type, filtration mode and operation conditions (e.g. crossflow velocity). Besides, exploration of synergetic influences of surface micro-patterning and feed spacers (bi-planar net typically employed in spiral-wound membrane modules to allow inter-membrane spacing and create flow channel between membrane sheets) on bio- and colloidal fouling is necessitated to assess the applicability of these new membranes at industrial level.

Particle imaging velocimetry (PIV) is a visual characterisation technique, in which fluid characteristics and particle deposition behavior can be qualitatively investigated (Haidari et al., 2016). 2D-PIV system equipped with reverse osmosis

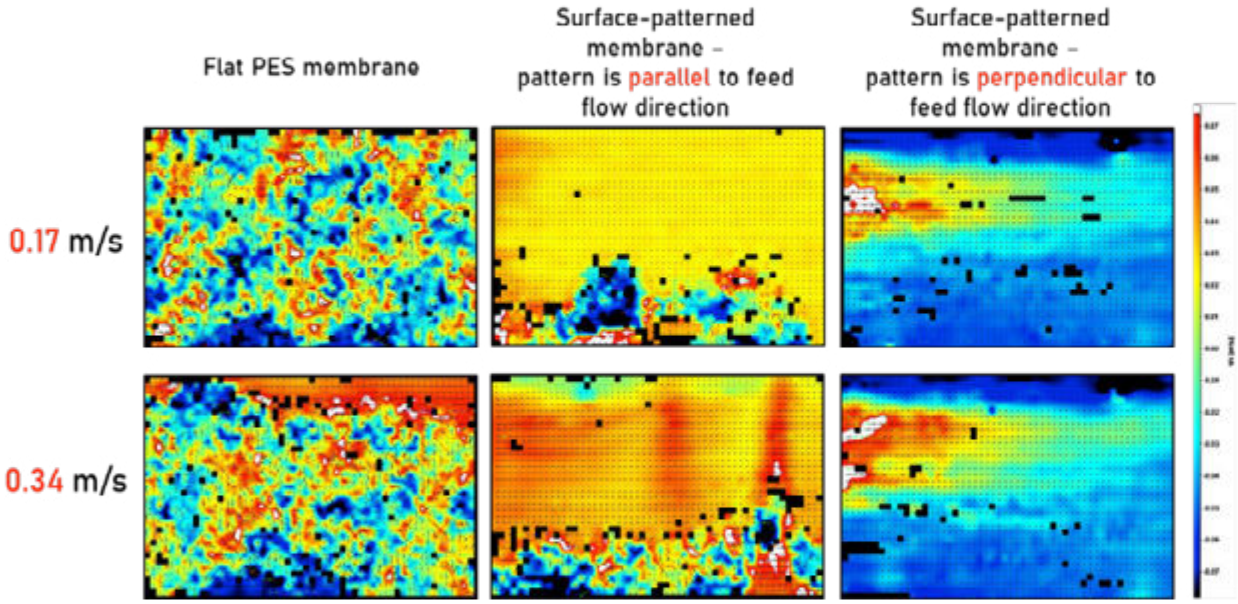

Figure 3.3 Momentary velocity profiles for fluid atop surface-patterned vs. flat membranes (at no permeation) at middle of PIV-RO cell for two crossflow velocities 0.17 m/s (Re = 191) and 0.34 m/s (Re = 382)

system (PIV-RO) has been successfully employed to investigate the impact of surface microstructures on fluid characteristics and particle fouling, at no permeation condition, using different crossflow velocities within laminar flow (Figure 3.3). Surface-patterned membranes at parallel orientation have exhibited substantial homogenous flow stream with enhanced fluid mixing, compared to flat membranes, which resulted in lower model particles' deposition. In contrast, surface microstructures at perpendicular orientation led to significant fluid deceleration accompanied with poor fluid mixing. Moreover, recent examples have been reported in literature on studying fluid characteristics in spacer-filled channels based on conventional TFC membranes (Haidari et al., 2018a; Haidari et al., 2019b). In the next phase, PIV-RO will be employed to study fluid characteristics and spatial particle distribution in spacer-filled channels based on surface-patterned TFC membranes.

Behaviors of nanoparticles in environment/treatment processes

Research has shown clear evidence of nanoparticle (NP)-specific effects on organisms and ecosystems, and key parameters that control the spatial and temporal distribution and form of nanomaterials in the environment have been investigated. It is now clearly understood that that NP of incidental (e.g., smoke stacks) or natural origin are ubiquitous, many orders of magnitude more prevalent, and often similar or identical to many engineered nanomaterials. Studies of the fate and effects of natural and engineered nanomaterials in complex environmental systems have highlighted the critical role of nano- and microphase materials in biological responses to contaminants and in resulting ecosystem function. This progress points to a key knowledge gap in understanding the broader role of nano-scale materials, most often of natural or incidental origin, in interactions with organisms and ecosystems. An important lesson learned from these research efforts is that convergence of expertise from experimentalists, modelers, data scientists, spectroscopists, and others is essential for elucidating the role of nano and microphases in biological function and ecosystem response.

An array of transformations (e.g., reactions with biomacromolecules, redox reactions, aggregation, dissolution, sulfidation, biodegradation) that occur in the environment has been elucidated (Cheng et al., 2011; Kirschling et al., 2011; Levard et al., 2011; Gondikas et al., 2012; Lowry et al., 2012; Ma et al., 2012). These findings indicate the need to consider the rates and extents of multiple interlinked transformations in real environmental media when assessing the bioavailability, environmental risks, and safety of NP. It was indicated that the original macromolecular coating on NP and the coating they acquire greatly influence their chemical, physical, and biological behavior (Li et al., 2010; Deonarine et al., 2011; Bone et al., 2012; Unrine et al., 2012). It was hypothesised that in the environment, interactions with NOM proteins or other biomacromolecules will dominate NP behavior from transport to biouptake.

Analogous to the use of the octanol-water partition coefficient in predicting the environmental distribution of organic chemicals, and the propensity for NP to attach to given surfaces can be used to predict NP transport and fate (Espinasse et al., 2018), and bioaccumulation (Geitner et al., 2016; Geitner et al., 2019). Methods have been developed for practical lab-based methods (Barton et al., 2014) for quantifying attachment (or surface affinity) coefficients (Geitner et al., 2017) and the underlying theory that governs these interactions (Lin and Wiesner 2012a; Lin and Wiesner 2012b). Fundamental new theory and models that describe interactions for very small particles (where assumptions often made in colloid science do not hold) have also been developed (Lin et al., 2012).

Conclusion

This report summarises several topics related to particle separation processes. Progress is being made in conventional processes and much more efficient recovery of resources from wastewater should be carried out. Resource recovery from wastewater by efficient particle separation processes is accelerating in many regions of the world. Manufacturing new materials (e.g., anti-fouling membranes) would further facilitate this trend. The monitoring of particles in environments needs to be improved to adequately understand and assess the impacts caused by them. Regarding NP, the grand challenge remains of sifting through a staggering diversity of nanomaterials, with countless variations in size, shape, surface chemistry, chemical composition, coatings and composites. Moving forward, there remains much to learn about the relationship between the vast array of nanomaterial properties and their potential environmental exposure, biological effects, and ecological consequences.

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| 3.4 |

Sludge management

It's time to look at sludge management with a new perspective*

Authors: *Ludovico Spinosa, Puja Doshi on behalf of the Sludge Management Specialist Group.*

Introduction

Across the world, 2.4 billion people still lack improved sanitation facilities and 1 billion people still practices open defecation. This is a well-recognised challenge that is reflected in Target 6.2 of the Sustainable Development Goal (SDG) of the UN Agenda 2030 which is addressed to "achieve access to adequate and equitable sanitation and hygiene for all…".

To achieve above Goal it is necessary to reconsider the wastewater and sludge management systems to tackle the 21st century challenges, such as population rise, rapid urbanisation and depletion of natural resources.

Extended sewerage, new installations and up-grading of existing facilities are, therefore, to be expected, thus resulting in increased sludge amounts. However, sludge management is often considered the last wagon of the water cycle train, forgetting that the most appropriate treatment sequence to be adopted for the wastewater treatment is strongly driven by the available sludge reuse/disposal option(s). It follows the need to look at sludge management as the locomotive of the water cycle train to develop more sustainable strategies oriented towards maximising recovery benefits instead of those aimed at simply disposing of sludge.

This new perspective can be depicted as an ancient temple (Figure 3.4) where the locomotive/last wagon concept acts as base/underlying principle, technical and governance aspects as columns/supporting actions, fundamental principles as roof/overarching concepts, and boundary conditions as staircase/accessing steps, strictly depending on the technological, economic and social levels of the local actual contexts (Spinosa et al., 2017).

Fundamental principles

Fundamental principles include the sustainability and circular economy concepts, both subject to the principles of thermodynamics.

All human-operated transformations are not perfect or fully reversible and subject to the three principles of thermodynamics, according to which energy is invariably conserved (1st law), entropy, that is a measure of the disorder in an isolated system, constantly increases (2nd law) and absolute zero, i.e., a 100% recovery, is impossible (3rd law).

The basic concept of sustainability is that consumption of renewable resources should not exceed nature's ability for their replenishment. Furthermore, sustainable systems must be environmentally bearable, economically convenient, and socially acceptable, and this means that the sustainability concept includes social issues (Figure 3.5).

It is important to observe that sustainability must be seen from a relative, not absolute point of view, because it strictly depends on how the boundaries, which should include all the operations composing the system, are set (Spinosa and Doshi, 2020). The greater the extension defined by the boundaries, the greater the sustainability of the system "as a whole", i.e., a single equipment/action cannot be defined as sustainable by itself without considering upstream and downstream equipment/actions of the operational cycle. Sustainability evaluation should also include alternative options to tackle local market variability (Spinosa, 2013).

The main problem for sustainability evaluation is that a clear and unique theoretical meaning is not supported by widely accepted quantification procedures (Spinosa and Doshi, 2020).

**Based on*
(1)presentation at ECSM 2019 – 5th Eur. Conf. on Sludge Man, Liège (B), 6th-8th October 2019
(2)publication in J. Env. Management, 287, 112338

Figure 3.4 Graphical representation of the new sludge/biosolids vision based on structural elements of an ancient Temple:
A - Underlying principle (Locomotive/Last wagon concept)
B - Columns / Supporting actions (Technical and Governance aspects)
C - Roof / Overarching concepts (Fundamental principles)
D - Staircase / Accessing steps (Boundary conditions and Barriers)

Figure 3.5 Conceptual representation of sustainability

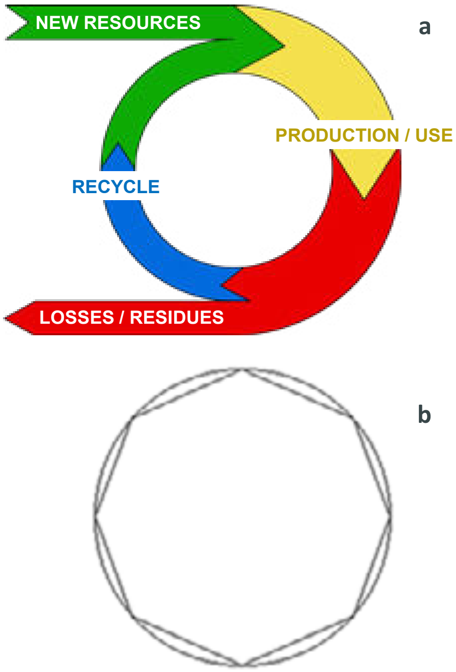

Figure 3.6 Representation of circular economy
(a = Principle; b = Approaching a circle through a polygon)

Circular economy can be defined as a system designed to regenerate itself. This conceptual definition must, however, consider that each cycle is inevitably characterised by some losses (Figure 3.6a). The challenge is to reduce the losses, and the consequential need for new resources, taking into consideration that the dynamics of the recycle/disposal flows are different from those of acquiring new resources.

Intuitively, circular economy appears to be more sustainable than the current linear economic systems (less losses, less emissions), but the social dimension of sustainability is only marginally addressed and potential trade-offs are needed to approach a series of linear processes to a circular system. Figuratively, a circle can be approximated with an n-sided polygon, each side representing a single linear process (e.g., dewatering), in case sub-divided into sub-processes (e.g. conditioning, dewatering machines construction, etc.), so the higher the number of sides, the greater the approximation to a circle with consequent maximisation of recoveries and minimisation of losses (Figure 3.6b).

Boundary conditions

Boundary conditions are directly linked to the specific context where management takes place and can be described by three pairs of terms: problem/solution, past/future and disposal/recovery.

Sludge management is generally seen as a problem, while it often derives from the solution of an original scarce availability of running water for civil and industrial uses, because the greater the quantity of water made available, the greater the quantity of wastewaters to be treated with the consequent problem of larger sludge amounts to be managed.

The terms past and future are clearly related to time units, but should also be related to place units, because the practical implementation of the development objectives differs according to the specific local infrastructural, economic, environmental and social contexts, i.e., at the same time some solutions can be adopted in some countries, but not in others (Spinosa, 2013). Finally, the general objective of developing sustainable strategies requires a shift from solutions aimed at disposing of sludge to those oriented towards maximising recycle or recovery benefits which are highly context-specific.

In conclusion, the production of sludge with the appropriate qualitative and quantitative characteristics strictly depends on the local specific situation.

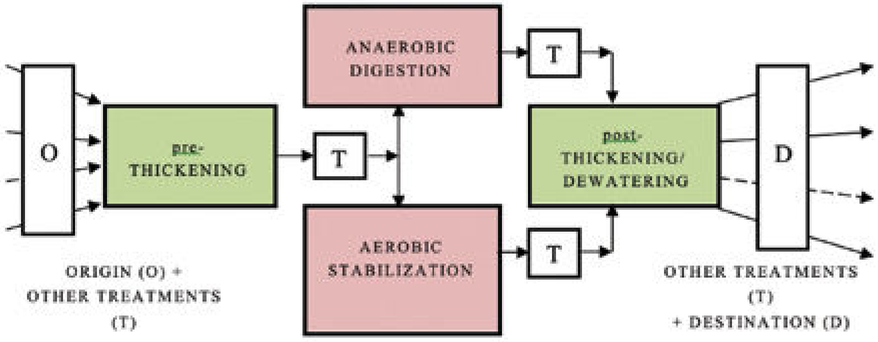

Figure 3.7 Technical "hubs" in sludge processing from origin to destination

Technical aspects (status and trends)

Maximising *recovery benefits* is the major prerogative to achieve sustainable wastewater and sludge management systems.

Regarding the recovery of materials, the nutrient content of sludge is of high value, so utilisation in agriculture (directly or via composting) is likely to remain the major option, especially where sufficient land for spreading is available and sludge is less contaminated. Nitrogen can be mostly recovered from treatment reject waters, while phosphorus through anaerobic digestion or from incinerated ash. Innovative technologies for P recovery from sludge ash are discussed in Abis et al. (2018).

Other material recovery includes the production of organic compounds (VFA, polyhydroxyalkanoates, enzymes, etc.), coagulants, adsorbents, bricks, pumice, slag, artificial lightweight aggregate, ceramsite, and Portland cement (Tyagi and Lo, 2013).

Available options for energy recovery range from anaerobic digestion to thermal processes, the latter also having the advantage to reduce the sludge volume and destroy toxic organic compounds. Technologies, such as wet oxidation, pyrolysis or gasification can generate energy and produce usable/storable fuels and char, but there are still some uncertainties about their performance and cost. The use of microbial fuel cells (MFCs) to directly convert sewage sludge to electricity, by-passing the production of biogas, has been demonstrated but, again, there are still some key issues with their commercialisation (costs, cells lifespan, efficiency, etc.) (Taşkan et al., 2020).

Within this context, the *reduction of nuisances*, through stabilisation/digestion, and the *reduction of volume*, through thickening/dewatering, represent two unavoidable *hubs* in the sludge journey from origin/production to destination/utilisation/disposal (Figure 3.7). Most of the stabilisation/digestion methods also reduce the sludge amount by degrading volatile solids.

The Reduction of nuisances is linked to sludge stability. Sludge can be stabilised by physico-chemical (lime addition, drying, irradiation) or biological (aerobic, anaerobic digestion) processes. A preferable method is the anaerobic digestion as it allows energy recovery by transforming organic matter into biogas.

In addition to the adoption of specific operational procedures, e.g., temperature optimisation (Gebreeyessus and Jenicek, 2016), ways to improve digestion performance include the following:

- *Pre-treatments*, aiming to modify sludge properties through enzymatic, mechanical, thermal, or chemical disintegration methods for a more effective process (Zhen et al., 2017).
- *Post-treatments*, by the addition of chemicals (e.g. lime), physical treatment (UV, irradiation), and biological post-aeration of digested sludge (Vojtiskova et al., 2019).

Aerobic stabilisation is an energy-consuming process quite easy to be operated. Developments include thermophilic conditions, or combination of a primary auto-thermal thermophilic aerobic digestion with an anaerobic mesophilic one.

Other field of research include (i) presence and fate of estrogenic compounds, (ii) effects of microbial enzymes, and (iii) molecular methods to understand microbial community structure and metabolism. The *Reduction of volume* is a pillar for the development of sustainable sludge management systems. However, the goal should not be pushing towards the production of an *absolute minimum* but, instead, making sludge amount *compatible* with its final destination and the best overall energy/material balance.

To this end, appropriate technologies within the wastewater treatment stage (cellular lyses, higher sludge age, ozonation, membrane technology, etc.) and/or the sludge treatment stage (thickening and dewatering) can be adopted.

The most significant progresses to improve the solids concentration include the following:

- Development of more effective chemicals to both decrease the solids content in the return waters and improve sludge concentration, and use of biopolymers to decrease the environmental impact (Wei et al., 2018).
- Improvement of performance of existing solid/liquid separation technologies to reduce water, air, energy and chemical consumption, odour and noise level (Wakeman, 2007).
- Development of new technologies based on combination of mechanical and other forces (electrical field, thermal supply, ultrasounds) to get higher volume reduction with the best energy efficiency (Tuan et al., 2012).

Thermal treatments have gained interest in recent years, but while combustion processes are already applied at full scale, pyrolysis and gasification still require further studies before wider application.

Governance aspects (regulation and barriers)

The transition towards a new perspective of sludge management also requires attention to the often underestimated governance aspects.

The development of realistic and enforceable regulation is crucial because an environmentally safe sludge management can only be achieved through objective, transparent, and legally conducted operations (Spinosa and Vignoles, 2012). Regulation on sludge (i) covers vertically the range from local to national ones, (ii) falls horizontally under health, planning and building sectors (Johansson and Kvarnström, 2005) and (iii) needs to be adapted to the local context.

Within this context, the imposition of generic and not numerically quantified limits (difficult to be controlled and prosecuted), and/or unjustified limits (which could become dangerous) must be avoided. Further, some countries have well-developed legal systems, but the ability to enforce laws is weak, and vice versa.

Regulation needs to be supported by standardised characterisation procedures and guidelines of good practices, because well-defined procedures allow legal requirements to be fulfilled in a correct and uniform manner, thus building stakeholder and public confidence.

The volatile (VS) to total solids (TS) ratio and/or the VS reduction is a simple and fast method, also for field measurements, for stability evaluation, but several other possibly more complex or longer parameters/methods can be used. They include BMP (biological methane potential), OUR (oxygen uptake rate), odour intensity, Emission of specific odorous compounds, TOC, BOD_5, COD or BOD_5/COD concentration in the water separated from the sludge, C/N ratio.

Parameters for characterisation of sludge thickenability/dewaterability include SVI (Sludge Volume Index), CST (Capillary Suction Time), SRF (Specific Resistance to Filtration), Compressibility, Settleability, Thickenability, Drainability index, Limit dryness, Centrifugability, etc. (Ginisty and Spinosa, 2016).

However, most of above-mentioned parameters are specific to a method of treatment, but not able to give basic information on sludge behaviour. In this field, great advancements can be expected by the utilisation of parameters like the rheological properties, particle and floc size distribution and water distribution (Spinosa, 2016).

As already mentioned, sludge management system is a context-specific issue (Tilley, 2014), so local circumstances play an important role in sludge management. They include climate conditions, political and cultural aspects, market structures, and the availability of tools some of which could be not available everywhere (Lüthi et al., 2011). The distinction between rural, peri-urban and urban areas or formal and informal settlements, e.g. slums, is relevant to find the right solution.

Legal pluralism is characterised by the co-existence of rules from different origin and legitimation, that often leads to an overlapping of customary, religious, national and even international principles/laws (von Benda-Beckmann, 2007). The distinction between official (de-jure) rights and effective (de-facto) rights helps to understand why in certain situations the formal acceptance of law doesn’t necessarily mean that law is applied in practice (Johansson and Kvarnström, 2005).

In addition, barriers towards accessing water, wastewater and sludge systems need to be understood. Exogenous factors, e.g. economic access to public systems, and endogenous factors, e.g. taboos towards handling of human waste, may act as barriers.

Costs may act as a barrier for many low-level households to enter the system, so solutions for integrating poor households are crucial. An increasing block tariff, as promoted by the World Bank since the 1970s, is a price structure in which a commodity is priced at a low initial rate up to a specified volume of use (e.g. 25–50 l/cap/d), then at higher rates for additional blocks used.

However, this system of pricing mechanisms could result in adverse effect because the assumption that every household owns a water meter does not reflect the reality in many developing countries, where many households in highly dense populated areas share one water meter, thus entering higher rates, or even none, thus resulting in illegal water trade.

Finally, the development of an institutional system that promotes sustainable systems and circular economy is necessary for the establishment of an adequate and effective governance system. This political process develops along three lines: (a) normative aspects, (b) social embeddedness of the economy and (c) institutional changes (Moreau et al., 2017).

The normative aspect is basically the institutional setting (rule of the game), the social embeddedness implies that the institutional conditions need to be accepted by the people in terms of social norms, while the institutional changes can be described as the game of the rules (Moreau et al., 2017). Institutional syncretism interweaves old/new, traditional/modern, informal/formal elements in a creative process to form a completely new type of institution. If this creative process becomes part of the political process, sustainable systems and circular economy can be successfully implemented by continuing old institutions under new conditions while acknowledging endogenous (embedded social norms, morality values, etc.) and exogenous (costs, poverty, etc.) access barriers.

Digitalisation can be of great help as it (i) allows greater operational capacity through real time monitoring, (ii) helps utilities to make investment decisions based on assessment capital and lifecycle cost of assets, reducing expenditures and (iii) can support communication between citizens and local institutions thus ensuring greater transparency.

Conclusions

To allow an effective sustainable sludge management by ensuring maximisation of sludge value, it is time to look at sludge management with a new perspective where (i) sludge is considered as the locomotive, not the last wagon, of wastewater systems, (ii) both technical and governance aspects are considered and (iii) any action must comply with general basic principles and fall within defined boundary conditions.

Main technical aspects require us to (i) assess management routes capable of maximising recycle/recovery benefits, (ii) use technically, ecologically and economically feasible methods to reduce sludge quantity at the appropriate level and to improve sludge quality and (iii) develop operational systems appropriate to local and site-specific circumstances.

From the governance point of view, a sustainable sludge management system requires the (i) development of realistic and enforceable regulation, (ii) definition of standardised characterisation procedures and guidelines of good practice, (iii) development of approaches tied to specific local technical, economic, political and cultural priorities, (iv) understanding endogenous barriers and (v) establishing institutional systems and political processes to promote sustainable and circular economy approaches.

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| 3.5 |

Small water and wastewater systems

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Introduction

Today, around 80% of all wastewater is discharged untreated into rivers, lakes, and oceans. It creates health and environmental hazards, and contributes to greenhouse gas emissions, including nitrous oxide and methane. These emissions are three times larger than those produced by conventional wastewater treatment activities. Recovering water, energy, nutrients, and other precious materials embedded in wastewater is an opportunity for cities to transition to the circular economy and contribute to improved water security. All wastewater treatment systems begin with the basic premise of wastewater collection followed by treatment and disposal. There are several collection, pre-treatment, treatment, final disposal, or water recycling options for communities. Communities have a wide variety of options to provide the best treatment in the most cost-efficient manner. Typical residential water usage is from 75 to 135 litres per person per day. Eighty per cent of the population is connected to a centralised (municipal) wastewater collection and treatment system, while the remaining 20 per cent uses on-site septic systems.

When a community faces wastewater treatment issues, a successful outcome is often dependent on the process the community follows to address the issue than it is on the sewage treatment technologies available to them. Most importantly the successful implementation of technology depends on how the community vision and participation. The other factor for consideration is change acceptance encouraging leaders, who initiate small systems, locating needed technical and financial resources, and taking time to document successes and reward participants. There are numerous examples available of Minnesota communities providing community–wide services involving mechanical or pond systems, or separation technologies for treatment followed by soil sub-surface, soil surface or surface water final dispersal. There are many examples of communities that allow individual, cluster (multi-home) systems or a combination of various options. Communities facing wastewater infrastructure improvements have the difficult task of identifying the appropriate technologies to meet their needs. This tool may be used to begin identifying some of the many choices available. The best fit for individual communities depends on many factors. These include assessing the community needs, current situation, evaluating soils, drinking water availability and quality, evaluation of existing wastewater treatment systems, community factors such as anticipated growth, desired community goals, community values, financing options and management options. The whole purpose of wastewater treatment is to treat for contaminants and recycle to the water cycle; in some cases the treated water can be used for something else, called reclamation.

Small systems seem a logical solution to tackle sustainability problems of wastewater management systems, because they focus on the on-site treatment of wastewater and on local recycling and reuse of resources contained in domestic wastewater. Decentralised solutions in general will tend to be compatible with local water use and reuse requirements, where locally treated water could support agricultural productivity or (in more urban areas) be used as a substitute for drinking-quality supply water for compatible uses. In analysing sustainability of technology, different dimensions should be considered (in particular, local issues). There is no fixed or universal solution to the technological issue; on the contrary, all relevant studies demonstrated there are varying degrees of sustainability in the way a technology is selected and operated, to avoid exporting problems over time or space.

Traditionally the argument for economies of scale has been for centralising wastewater treatment plants (WWTPs). Therefore, research has mainly focused on large-scale systems, resulting in a wealth of available operating data and a firm understanding of their overall performance. By contrast, smaller SWWTPs are typically overlooked. This may be because they are often only used where there is no other economically viable option, their perceived environmental impact is localised, and/or they may be exempt from regulatory conditions. This last point is of particular importance because regulatory compliance requires monitoring and more effective management. Without mandated monitoring, limited performance data have historically been collected, which now restricts our ability to predict performance and estimate potential discharge impacts.

Reliability

The treatment performance of small wastewater treatment plants (SWWTPs) is not well understood, and their ecological impact may be underestimated. Growing evidence suggests they play a critical role in ensuring sustainable wastewater management, meaning they can no longer be neglected. A study for a year operation on a community SWWTP, indicated that the removal rates for COD soluble, total suspended solids and ammonia was ranging at 67%, 80% and 56% respectively with a standard deviation of 30%. Whereas in larger systems the equivalent rates were 73%, 92% and 94% respectively with a standard deviation of 5%. The data show that the reliability of small systems depends on population equivalence, suggesting the smallest WWTPs may require particularly stringent management. Growing awareness of the need for sustainable wastewater and water resources management makes this approach both timely and widely relevant.

Limited understanding of SWWTPs is driven largely by a lack of available operational performance and impact data. The stability and effluent quality of smaller systems is significantly poorer than their larger counterparts. A study indicate that, the influence of size extends beyond what has been previously recognised, especially how system size relates to consistent compliance with possible limits. While we talk about the technology for small systems, For example, the smallest WWTPs (50–125 PE) appeared less stable than the slightly larger WWTPs (125–250 PE), across all technology types. Package plants, especially RBCs, provided more stable treatment performance and better effluent quality overall. These trends were also reflected in the reliability of the different systems. Mathematical models and techniques can be used to a reasonable degree of accuracy which might improve operational efficiency. Such analysis can inform a more strategic approach to managing effluent releases in rural and remote catchments, particularly to achieve regulatory compliance, reduce environmental impact, or prioritise operational and capital investment. Prioritising interventions across a system of small WWTPs is essential if environmental aspirations are to be achieved cost-effectively. There is a growing recognition of the benefits of decentralised wastewater infrastructure by applying proper control and monitoring systems.

Resource recovery and circular economy

SWWTPs are used to treat and dispose, at or near the source, relatively small volumes of wastewater, originating from single households or groups of dwellings located in relatively close proximity (indicatively, less than 3–5 km, maximum) and not served by a central sewer system connecting them to a regional WWTP. This obviously still needs a local collection system, yet this will likely be much smaller and less expensive than those used for conventional, centralised treatment, especially when the greywater components have been separated from the black flow (as discussed in a later section. The small systems also qualify in serving small portions of urban areas. Sustainable small systems sanitation focuses on the on-site treatment of wastewater and local recycling and reuse of resources contained in domestic wastewater (in primis, water itself). It has been claimed that small treatment systems favour water recycling and reuse in proximity of their location. Other resources that can be readily recycled are, bio-energy (mostly from organic material transformation, even though attempts are being made to recover water-embedded residual heat), and nutrients (mainly nitrogen and phosphorus). Also, in these cases local reuse of recovered components helps to form “closed loops” of resources uses, in line with the principles of circular economy. To reduce use and wastage of resources, typical of a “once-through” resource use, the “closed loop” concept was introduced, whereby system resources, energy, and materials are re-used multiple times (even if for different purposes) with minimum processing required by each subsequent use. The circular economy is a new global economic paradigm that, looking beyond the current “take, make, and dispose” mode, is designed to be restorative and regenerative and, relying on system-wide innovation, aims to redefine products and services to eliminate waste, while minimising negative impacts.

Small water and wastewater systems Specialist Group

The specialist group deals with water and wastewater systems serving individual houses, a cluster of houses or a community. The group considers the use of localised systems will help in recycling and reuse of wastewater. This will also enhance and promote the closing of water and nutrient cycles. The group believes that water and sanitation can be made available to the entire population of the world only by adopting localised systems. This will enable people’s participation in the control and management of the systems. Recently, package systems for supply of water and treatment of waste including industrial waste have become available and accepted by communities all over the world.

The recent conference at Murdoch University, Perth, Western Australia, drew attention to small systems and the challenges faced in their implementation and maintenance. The specialist group on resource oriented sanitation presented technology to recover and recycle nutrients from wastewater systems. The conference recommended that onsite or decentralised systems are still more reliable and maintainable looking at socio economic benefits.

Challenges and the way forward

The drivers for centralised or decentralised systems are the following: (1) energy cost; (2) compliance with greenhouse gas emissions; (3) availability of land; and (4) effectiveness and efficiency of systems for recovery of nutrients. The first expectation is that the effectiveness and efficiencies of treatment systems should allow much less waste and make better use of resources. Innovative technology to reduce energy costs is needed to reduce costs of operation. Vacant land is less available for the increase in population and to incorporate a wastewater treatment plants in development. Probably this is where downsizing centralised systems to small ones could work better. Wastewater treatment plants generate greenhouse gases. The future challenge is to design plants that consume less energy and create a process that will reduce emissions or recover and reuse these gases without releasing them to the atmosphere. It would be good to think that water demand and treated wastewater, removal of pathogens and innovative bacteria growing methods could use less energy. However, it may be difficult to address all the challenges for the next 20 years but we can definitely establish a plan for the next 5 years and one that addresses the above factors. Wastewater reclamation, reuse, and resource recovery have been used in limited applications so far, but they will become a necessary, generalized fact of life if a sustainable future is envisioned.

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| 3.6 |

Statistics and economics

Towards a circular economy model

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Introduction

The circular economy (CE) is a model of production and consumption that involves sharing, renting, reusing, repairing, renovating and recycling existing materials and products as many times as possible, minimising the generation of waste and reducing the demand of raw materials. The implementation of a CE model in the urban water cycle is not only a more efficient strategy, but also gives the opportunity to develop new and innovative businesses and protects the whole production system from the scarcity of water, while guaranteeing the sustainability of water resources and the environment. Although both public and private administrations have already started to move from a linear economy model towards a circular model, there is evidence that there is still a lot of room for improvement as far as implementation is concerned. It can be said that the transition to a circular economy model in the water sector has been slowed down not by the lack of available technologies to carry out the processes necessary to recover the product from the urban water cycle, but by social, institutional, and economic aspects. To succeed in the application of a circular economy model a holistic approach that takes into account political, decisional, social, economic, technological and environmental factors is needed. For this reason, lately, the Specialist Group on Statistics and Economics has included this topic in the agenda.

Existing knowledge

Our society is facing a water security crisis (Grey and Sadoff, 2007), which can be understood as the availability of an acceptable quantity and quality of water for health, life, ecosystems, and production, coupled with an acceptable level of water-related risks to people, the environment and the economy. To face this crisis and guarantee the sustainability of water resources and the environment, a transition to a circular economy model is needed.

Up to now most economy systems are linear and follow the scheme of ‘take-make-use-dispose’ in which materials and products have only one use and waste is usually the last stage of the product life cycle. However, circular economy models intend those products and material remain in the economy cycle as much as possible, while waste generated in the production process be treated as secondary raw materials that can be recycled and re-used (Ghisellini et al., 2016). Thus, it can be said that circular economy promotes sustainable management of materials and energy by minimising the generation of waste an promoting their reuse as secondary material (Neczaj and Grosser, 2018).

According to Kirchherr et al. (2017), CE is most frequently depicted as a combination of reduce, reuse, and recycle activities and seeks the following purposes:

- to use the minimum amount of natural resources needed to meet the needs required;
- to avoid non-renewable resources and critical raw materials favouring the use of recycled ones;
- to carry out an efficient management of the resources used to maintain and recirculate them in the economic system for as long as possible;
- to reduce environmental impacts, as well as restore natural capital and promote its regeneration.

There are many technologies and practices that can help us move to a circular economy in the water sector, some of these are: collecting rainwater from roofs and using it to irrigate landscapes or for other purposes, recycling wastewater from baths, showers, sinks and washing machines for use in toilets, landscapes and other applications, using recycled water for industrial processes, agriculture and other purposes, treating wastewater to remove pollutants and make it safe for reuse, using natural features, such as plants and soils, to capture and treat stormwater runoff. However, the main limitation of the circular paradigm is not technology development but social, institutional and economic barriers. Regarding social barriers, it has been found that our society resists to use reclaimed water mainly for risk perception, cultural reasons, or the lack of awareness of the potentialities of reclaimed water as a resource (Gul et al., 2021). This aspect has a direct impact on the development of a market for reclaimed water. Reclaimed water needs to be conditioned before being used and it requires advanced technology and economic resources to produce and deliver it to the final user, therefore if there is no demand that permits to recover the costs of reclaimed water production the circularity of the resource cannot be guaranteed putting at risk the sustainability of the entire urban water system.

We should bear in mind that one of the most relevant aspects of water management is the financial sustainability of water utilities. For water utilities to be financially sustainable, it is important that they have a stable and predictable source of revenue. That is, water utilities need to generate enough revenue to cover their costs. Cost recovery can be achieved through a variety of methods, such as user fees, taxes, and subsidies. One of the main sources of revenue for water utilities is user fees. In most cases, user fees are based on the amount of water used. Water utilities in developed countries typically have a volumetric tariff, which means that the user is charged based on the amount of water consumed. User fees could also include a social component based on the ability to pay which purpose is to enable the economic access to water for everyone. According to Pueyo et al. (2019) the tariff system of the urban water cycle must be global self-financing and cover all the costs incurred in the activities and processes involved within the urban water cycle management. In some cases, the government will impose a tax on the water utility in order to generate revenue for the government. And the third source of revenue for water utilities is subsidies. Subsidies are payments from the government or another institution to a water utility to help finance the costs of providing water services. Subsidies can be in the form of cash payments or in-kind payment, which are payments in the form of goods or services. Regardless the mechanism or the combination of mechanism applied to achieve the cost recovery of reclaimed water projects, this principle cannot be underestimated, since the sustainability of water resources depend on it.

In particular, the Water Framework Directive (2000/60/EC) (European Commission, 2000) claims that cost recovery has not only economic implications, but it is also understood as the mechanism that would guarantee a sustainable, balanced and equitable water supply that meets the needs people and economic activities. Besides this, the Water Framework Directive, suggests extending the application of economic instruments to quantify the environmental costs and benefits integrating them in water tariffs. This is a very interesting approach to implement reclaimed water projects since the reuse of water has numerous benefits, all of them of great economic, environmental, and social relevance, but maybe the most obvious in environmental terms is that wastewater treatment plants become unconventional water sources that help to reduce the pressure on conventional water bodies. Another of these benefits consists of reducing the impact associated with the discharge of the effluent into the natural environment, since the quality of the water masses in the basin is preserved. Usually, the costs of drinking water and reclaimed water respond to the capital costs linked to the technology and the water infrastructure and the costs linked to the operational and maintenance of the service. Rarely, do they include environmental impacts or benefits regarding aspects such as resource scarcity/availability, contamination/water quality improvement. If those impacts/benefits were measured economically they would play an important role in the cost factor of conventional and non-conventional water sources. The cost factor can increase or decrease public acceptance of reclaimed water. For instance, if the price of conventional water sources includes the environmental impact that their use is generating, it would be more expensive than reclaimed water. Cheaper drinking water sources can increase public willingness for purchase and consumption. The new paradigm associated with the internalisation of environmental and social benefits within decision-making processes highlights the importance of the natural environment as a space whose dynamics change due to the management that society makes of it. On the other hand, the environmental and social benefits present strong synergies in common, because for society to be able to enjoy and obtain resources, the ecosystems must be conserved in optimal conditions, ensuring their long-term sustainability.

General trends and challenges

To achieve the objectives and principles of the circular economy it is necessary to go a step further and overcome a series of barriers and see reclaimed water as a potential source of water integrated in the urban water cycle. Therefore, there is a need that the projects about water reuse are not only technical feasible but also economic, guaranteeing the cost recovery. In parallel to all the economic efforts that should be made to guarantee the feasibility of reclaimed water projects, it is necessary to ensure public acceptance through the implementation of information and communication campaigns for users to transfer to society the benefits associated with this activity and to publicise the risks that it may pose to human health and the environment and the ability to manage them, for this it will be necessary to develop indicators that allow to measure the quality of reclaimed water, as well as indicators of sustainability in the use of water.

Finally, to promote the implementation of circular policies, particularly, it is important to emphasise several points that could contribute to achieve the purposes of circular economy:

- Encourage the reduction of water consumption.
- Promote the reuse of water for those purposes that do not require a high quality of water.
- Wastewater treatment plants should be understood as an alternative source of water and other products.
- Encourage the development of research and innovation of new technologies to achieve the challenges of the implementation of a circular economy model.
- The implementation of the urban water cycle processes with digital tools will enable data monitoring, processing, and management with great benefits in terms of water consumption and environmental protection.
- Data exchange among all the decision makers in the urban water cycle to guarantee the circularity of the process.
- Promote the use of economic instruments to value water and measure the environmental benefits that circular economy policies will bring.
- Clear legislation that establishes the framework for action.
- The user's acceptance of the water and his training so that they know the product they use.
- A good marketing strategy and communication policy about reclaimed water.

Conclusions

The water sector is one of the most important in the economy as it is necessary for human life, industrial production, public health, the environment and economic development. The provision and management of water resources is a complex and challenging task in technical, environmental, economic and social aspects. Therefore, a circular economy is an alternative to the traditional linear economy and offers a promising new way to meet the world's growing demand for water and other resources while protecting the environment. It can help reduce reliance on fossil fuels and achieve other sustainability goals, such as reducing greenhouse gas emissions and waste. The implementation of water reuse projects requires important investments to develop the infrastructures needed to treat and deliver the reclaimed water that should be integrated as another part of the urban water cycle, in both physical and economical terms. Nevertheless, the implementation of the urban water cycle with a water reuse system needs changes in the current system with social, economic and natural capital implications.

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| 3.7 |

Sustainability in the water sector

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Introduction to sustainability

Because sustainability is a basic underlying principle for the International Water Association, the history of the concept will not be outlined here. The IWA is committed to water sustainability and to the SDG adopted by the United Nations in 2015, which have converted the abstract concept of sustainability into more concrete and actional objectives. The work of the Specialist Group on Sustainability in the Water Sector reflects this commitment, as well as the growing awareness of the importance of more careful use of resources—creation of a circular economy where outputs from one process can become inputs into another.

Existing knowledge on topic

During the past several decades, great strides have been made in analysing relationships (e.g., the relationship between contaminated effluent from industry and environmental and community health), developing new technologies to address risks and support a circular economy, and anticipating the consequences of continued destructive and unsustainable practices. However, our technical knowledge is not matched by our knowledge on the behavioral side, and our knowledge on how to use water sustainably is not always translated into action.

The Specialist Group has worked toward concrete progress in more sustainable water use by focusing its efforts in four areas:

- implementation of the UN SDG;
- Professional development and staff training;
- sustainable use of water by industry; and
- digital water (with a focus on the digital worker).

Trends and challenges

Progress toward UN Sustainable Development Goals

Contributions from all sectors of society will be necessary for the world to make real progress toward the UN SDG. The Specialist Group on Sustainable Use of Water by Industry has focused on the role that utilities can play to support Sustainable Development Goals—not only those relating directly to clean water and sustainable use of water, but also additional areas such as the environment and the role of women whether the actions of utilities can make a difference. In Sustainable Industrial Water Use: Perspectives, Incentives, and Tools, sponsored by this Specialist Group and published by IWA Publishing in 2021, Troels Bjerre presented a strategic planning model used by the Danish water company VCS to explore and define the contributions it could make to SDG by integrating the goals into its strategic planning process. During 2021, the Specialist Group also provide a webinar on SDG to Young Professionals in Eastern Europe, to introduce the concept to them. Later in 2021, the Specialist Group provided, in partnership with the African Water Association, a webinar on the role played by utilities in Africa in supporting SDG (including support for the development of women by reducing the time they needed to spend acquiring and transporting water for household use).

Professional development and staff training

Historically the water industry has been more focused on infrastructure, technology, equipment than on the skills and abilities of the staff responsible for planning, building, operating, and maintaining them. Reliance on the acquired knowledge of experienced professionals has often been accompanied by inadequate investments in documentation, technical training, staff development, and knowledge transfer. The limitations of this strategy become apparent when generational staff turnover result in numerous vacancies, or when new technologies, policies, or regulations call for staff to learn new approaches. In developing countries, these difficulties may be compounded by low wages that result in continuing turnover, and educational levels that make it difficult for staff to handle management, administration, and operational tasks. While one aspect of the challenge involves training of managers and engineers, adequate staff development and training is an important issue at every level of the organisation, including skilled trades. Whatever opportunities may be available for more sustainable operations ultimately depend on workforce sustainability.

Continuous availability of both formal and informal professional development opportunities is imperative in todays' modern workforce. Webinars and podcasts are examples of informal learning that gives the participant control over when they seek assistance. That is partly why informal professional development programs are more impactful when combined with formal offerings (Meyer, 2017).

Professional development and staff training can be incorporated as a specific goal within many different types of activities. The Sustainability in the Water Sector IWA Specialist Group was a key sponsor and organiser of the IWA-IDB Innovation Conference on Cities, Industry, and Agriculture, held in Guayaquil, Ecuador , from 30 September to 3 October 2019; this even disseminated information to an international audience, with a high level of participation by conference attendees from Latin America. During this conference, a national chapter of the IWA and a Young Professionals Chapter for Ecuador were created, to encourage future collaboration in activities that would promote ongoing professional development. Technical sessions also provided the opportunity for information exchange among students, Young Professionals, and more experienced water professionals.

Since the need distance learning was multiplied by the pandemic, the Specialist Group has responded by supporting multiple webinars. Topics that have been addressed by the webinars have included the following:

- the UN Sustainable Development Goals (with a target audience of young professionals in eastern Europe);
- empowering women in the water industry (for women's gay in 2021);
- the role of utilities in supporting Sustainable Development Goals in Africa (in November of 2021); and
- sustainable use of water by industry (which was provided, in Spanish, in coordination with the university of Ghent and the IWA chapter in Ecuador in November of 2021).

The potential effectiveness of this tool has been well-illustrated by the webinar conducted to date, and should encourage continuing use of distance learning by IWA over time.

Sustainable use of water by industry

Industrial water use is a major consideration in water sustainability not only because of its quantity (20% globally and up to 50% in some countries), but also because of the disproportionate effect industrial water use has on communities and the environment. For example, release of inadequately treated effluent into water bodies adversely affects the health of vegetation, wildlife, and communities. The inadequacy of regulations and of regulatory enforcement in many locations encourages careless and damaging water use, while low water rates encourage excessive consumption. Progress has been made in several areas:

- Development of analytical frameworks and tools to assess sustainability at a watershed level (e.g., the Alliance for Water Stewardship framework and WWF's Water Risk Filter); and
- Development of new technologies for wastewater treatment, water reuse, and resource recovery.

The challenge is not lack of tools or technology, but the will and ability of businesses to use these tools and technologies. Barriers can include lack of awareness of improved practices and technologies, inadequate funding to invest in new technologies; staff who are not prepared to operate or maintain new technologies; and difficulty in making a business case for increased investment when water rates are low and regulations are non-existent or not enforced. Multi-national companies with international reputations to protect, and sufficient resources to invest in new technologies and staff training, provide a model for success. For businesses with less resources, less susceptibility to reputational issues, less oversight by regulatory agencies, and/or less will to protect the environment and people in their watersheds, the availability of tools and technologies are often a moot point.

During 2020, the combined efforts of the Specialist Group on Sustainability in the Water Sector and an IWA Task Group on Sustainable Use of Water by Industry resulted in publication of Sustainable Industrial Water Use: Perspectives, Incentives, and Tools. The book includes a wide range of perspectives, including those of private industry, government, educators, consultants, non-profit organisations, indigenous people, and utilities. Analytical and technical tools for improving sustainable use of water by industry are also provided. Additionally, the book discusses the combination of incentives, supports, barriers, and penalties that will be required to modify priorities and investments of private industry.

The book includes authors from all parts of the globe, including Latin American countries, and was used to support development of a webinar provided in Spanish (with support from the University of Ghent and the IWA Chapter of Ecuador) in the autumn/fall of 2021.

Digital water

For decades water and wastewater utilities have, with varying degrees of success, implemented a wide array of software and hardware tools. Computers have become as integrated into water and wastewater operations as valves and pipelines. Computerised billing systems, geographic information systems, system control and data acquisition systems, and knowledge management systems have been in use for decades. With changes that are now occurring in computing (e.g., in relation to artificial intelligence), the potential exists for water and wastewater services to be offered more efficiently, with more reliable provision of service to customers at a lower cost. Increased use of software and hardware tools can support sustainability in ways ranging from remote leak detection to water quality monitoring of effluents into water bodies or ecosystems that are the habitat of endangered species.

However, several components impact the sustainability and effectiveness of digital tools, as discussed below.

The development and introduction of digital tools often happens in isolation, without the use of reference architecture and available standards. This can result from lack of access to legal frameworks, lack of standardised applications, lack of qualified technical and administrative personnel, and the complexity of coordination and generation and utilisation of data. Water utilities often do not work together in these efforts, due to distance or inexperience in collaborative working relationships.

Even countries with significant wealth and experience in using digital tools often find it difficult to use these digital tools effectively. The Digital Worker: Effective Use of Digital Tools, published by BAYWORK, a consortium of US water/wastewater utilities in 2021, reflected challenges and lessons learned in the areas including selection of tools, organisational culture, human resource support, information technology support, coordination of workflows and processes, initial and ongoing staff training, development of qualified candidates with digital skills, cybersecurity, and artificial intelligence. The conclusion of that despite the potential benefits of digital tools, water and wastewater utilities are often not fully prepared to use them. All of these challenges also exist in developing countries, which can ill afford to purchase digital products that they lack the internal capacity to fully utilise.

Suppliers of digital tools often do not differentiate between the needs and capacities of different utilities, and utilities themselves are often ill-equipped to decide which digital tools they can benefit from in a sustainable way. As a result, there is often a significant gap between the theoretical capacity of digital tools and the actual benefit derived by the utilities and businesses that purchase and install them. Often digital tools are selected with an incomplete understanding of (1) the knowledge and skills that staff will need in order to be able to take full advantage of their features, (2) the ways that new systems will need to be coordinated with old systems and workflows, the Information Technology staff support that will be required for maintenance, (3) the openness of their organisational culture to learning and change, and (4) the level of staff time and investment that will be required to obtain the benefits desired. Frequently neither the vendor nor the customer has a complete understanding of the resources that will be required in order to fully utilise the tools.

In this area, IWA has a responsibility to balance its endorsement of the potential positive benefits of digital tools with resources to analyse their capacities and business needs more clearly, so that they can optimise their use of these tools.

Conclusions and research & development agenda

The IWA Specialist Group on Sustainability in the Water Sector plans to continue its focus on Sustainable Development Goals, Professional Development and Staff Training, Sustainable Use of Water by Industry, and Digital Tools, through a combination of workshops, webinars, and publications.

Progress is currently in process for a webinar on Empowering Women in the Water Industry for Women’s Day in 2022 (to be conducted in Spanish, with English translation), as well as a workshop on how the water industry can support women in the industry and in society in general for the IWA World Water Congress in Copenhagen.

The Specialist Group will participate in an all-day workshop on sustainable use of water by industry at the World Water Congress in Copenhagen, and will support a proposal for creation of a multi-Specialist Group IWA Task Group to address sustainable use of water by industry in the textiles, leather processing, and fashion industries. One of the proposed goals for the new Task Group will be to publish a White Paper and deliver presentations on the relationship between climate change and sustainable water use, and specific issues in the textiles and fashion industry.

An international workshop on the role utilities can play in supporting the Sustainable Development Goals is planned for the World Water Congress in Copenhagen, as well as a workshop on the challenges faced by utilities in making effective use of digital tools. One goal will be to develop a guidebook for utilities, to support them in analysing their own capacities and making more effective use of digital tools.

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Transitioning urban drainage

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Introduction

Urban drainage systems are key infrastructures in society, protecting public health and safeguarding the liveability of our cities. In developed and developing countries, approaches to urban drainage systems have evolved over the last 150 years into the systems we have today. Throughout history, there has been an ongoing debate as to the 'optimal' type of sewer system: combined versus separate. Combined sewer systems have the advantage of being robust and 'simple', but also have the downside of combined sewer overflow (CSO) emissions affecting receiving water quality. Separate sewer systems, on the other hand, have the theoretical advantage of lower receiving water impacts, but in practice the occurrence of illicit connections often transforms both the storm sewer and the foul sewer unintentionally into combined sewers. Combined sewers drain, depending on the design standards, 50% to 95% of the storm runoff to the central wastewater treatment plant (WWTP). Consequently, for pollutants that are removed at WWTPs at high rates, such as nutrients and organic matter, combined sewer systems may result in lower total emissions than separate sewer systems (Simon et al. 2018). This example illustrates that even for the most basic decision in urban drainage, 'should we opt for combined or separate systems?', the answer still remains: 'it depends...'. With recent trends to more and more treat stormwater runoff in decentralised solutions both combined and separate systems are transformed into hybrid systems. The idea is to relieve the pipe systems and to retain, infiltrate and evaporate stormwater instead. Increasing pressure from increasing rainfall intensities in a changing climate and increased pavement of surfaces in growing cities make such options even more interesting.

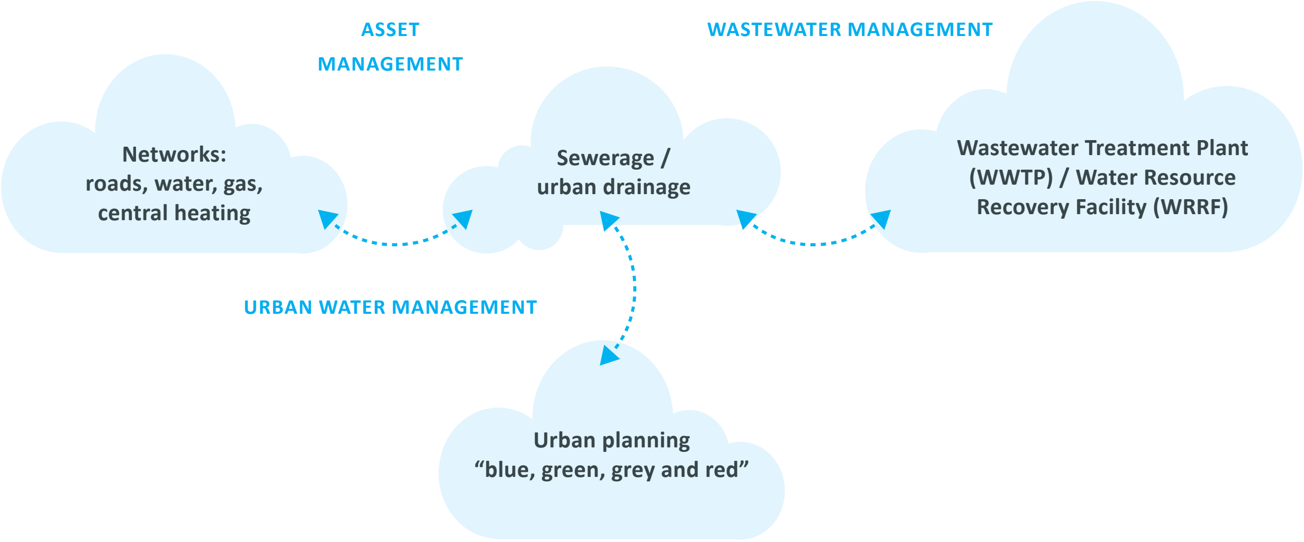

Figure 3.8 Directions for development of urban drainage infrastructure

Future trends

From an urban drainage perspective, there are three main topics directing urban drainage systems and involved organisations. The developments are depicted in figure 3.8 for areas that have been equipped with urban drainage infrastructure.

Identifying how, when and where urban drainage decisions, technologies and strategies can also contribute to achieving the UN SDG is also a growing research area.

Asset management

The first development is towards 'asset management'. Sewers are typically the most expensive underground networks in cities, followed by urban heating, drinking water, gas pipe lines and the cables for electricity and data communication. The Specialist Group on Strategic Asset Management and the JCUD Working Group on Urban Drainage Asset Management are developing knowledge, tools and processes to benefit from the existing infrastructure during its optimal service life. In practice, the adaptation of asset management practices often results in trying to minimise installation and maintenance costs (e.g., through multi-utility coordination of adjacent pipes), as the risks are more difficult to quantify. In general, this results in a focus on relining and replacing individual sections of network components, rather than evaluating whole system performance taking climate change adaptation and resource recovery into account, thus creating a dead lock for these developments. Increasingly, attention is being paid to minimise material use by extending service life and by reuse of pipes and pipe material. For example, PVC pipes will very likely be made from 100% of recycled material in the near future, which nicely fits in the circular economy.

Urban water management

The second development is 'urban water management', which nowadays focuses on climate change adaptation. There is a general consensus that traditional drainage systems designed to meet historic rainfall patterns will not be able to deal with the extremes of current climate change predictions: long dry periods and increased frequencies and volume of urban flooding. Consequently, a considerable amount of research is given to the development and implementation of novel concepts for dealing with stormwater (ranging from sustainable drainage systems (SUDS), low impact developments (LIDs), nature bases solutions (NBS), water sensitive cities, blue-green infrastructure to sponge cities (Jia et al., 2017) operating under differing climate conditions) by several of the working groups (WG) being part of the JCUD: SOCOMA WG, Water Sensitive Urban Design WG, stormwater management in cool and cold climates WG and storm water harvesting WG. There is now a consensus that storm water flows should be managed using systems that mimic natural processes, for example those that promote infiltration, flow retardation and storage close to source (which is tricky with, for example, man-made polders below sea level). Achieving this requires involvement of many disciplines, such as urban developers, landscapers, architects, and the managers of public space (urban green, roads) in urban areas. Reported barriers to successful implementation of "natural solutions" frequently include institutional fragmentation and split responsibilities as well as "path dependence" of organisational decision making favouring conventional grey infrastructures (Sarabi et al., 2019). Probably the most difficult issue to tackle in practice is to find enough space in the urban environment to deal with the increasingly heavy rainstorms. So, it is clear that more and more multiple benefits (also referred to as ecosystem services) of these systems to improve the biodiversity and microclimate become important to use the available public space in the most effective way. An often-overlooked aspect in this field is the management of groundwater. Insufficient attention to groundwater often results in high volumes of extraneous waters due to high infiltration rates to foul sewers or combined sewers, which negatively affects the potential for resource recovery at the downstream WWTP/WRRF (water resource recovery facility). Alternatively, urbanisation and its associated change of permeable to impermeable surfaces, can lead to falling groundwater levels, subsidence and – in coastal regions – saltwater intrusion with implications for current and future water security.

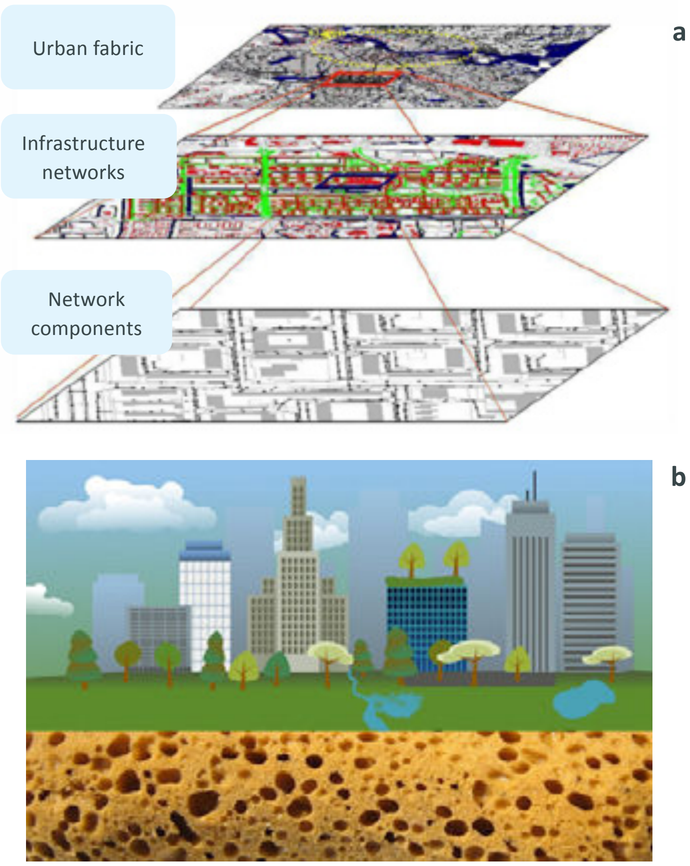

Figure 3.9 (a) Urban water management and (b) Sponge city (picture from Haifeng Jia)

Wastewater management

The third development is wastewater management, which has two objectives. The first objective is to minimise the impact of wastewater systems on receiving water bodies. This topic is the focus of the JCUD working groups real-time control of urban drainage systems, the international working group on data & models as well as the modelling integrated urban water systems (MIUWS) WG of the SG MIA (modelling integrated assessment). Therefore, treatment technologies for wastewater, stormwater and combined sewage are being developed as well as improvements for the operation (e.g., real-time control strategies with forecast systems) and modelling tools to test such developments.

The second objective is to contribute to a circular economy by increasing the recovery of wastewater resources (Grant et al., 2012). The type of sewer system and its operation influences the potential to recover water, energy, nutrients and other substances from wastewater sent to WWTPs, increasingly referred to as wastewater resource recovery facility (WRRF) to illustrate this new objective. Within the field of wastewater resource recovery, there are developments towards both decentralised sanitation as well as towards larger centralised and more advanced WWTPs. In decentral sanitation concepts, source separation is used to enhance the recovery potential. Interestingly, the development of concepts and treatment technologies occurs at a much higher rate than the potential transition rate of sewer systems towards source separated systems. For example, 15 years ago, the sanitation concept including urine separation received a lot of attention, while nowadays, mixing black water with kitchen waste to maximise energy recovery is a strongly supported concept.

The transformation of existing WWTPs into WRRFs, by adding post-treatment or additional treatment steps to recover water, energy or nutrients is slowly gaining importance. Its implementation requires legislative support to align alternative approaches to achieving resource recovering, with the ongoing development of an EU regulation addressing water reuse an example of a current initiative. Co-development of legislation and concepts/technologies is a major contribution to achieving circularity at a city scale. Also in this field, there is no consensus on the ideal type of sewer system and its performance. Despite the claim by many practitioners that WRRF influent should be as little diluted as possible, most resource recovery options take place via the sludge line, meaning that the dilution rate of the wastewater with extraneous waters or storm water is not very relevant. Moreover, recent dry summers in large parts of Europe have changed the emphasis of resource recovery to water recovery, thereby starting to compete with local storm and groundwater uses. To this aim, new concept of complementing conventional centralised treatment system with decentralised Nature-Based Solutions integrated within the urban water cycle is gaining some attention (Lafortezza et al., 2018). Local storm/grey/waste water treatment depending on local non-potable water needs offers new opportunities for water reuse and freshwater savings. Resource recovery typically focuses on creating a reliable additional source for water supply, while at the same time the remaining infrastructure, in most cases combined sewer systems, has to be able to deal with less flushing volume. It is up to the urban drainage community to guide this development in such a way that the recovery systems will flourish, while the existing urban drainage networks will be able to continue functioning reliably and without too many blockages or enhanced degradation.

Digitalisation, automation and interaction

Digitalisation is an ongoing development that started decades ago. While in many industry branches the use of “digital twins” are recent developments, in urban drainage the use of computer models for designing and optimising the systems has a long history. Nevertheless, in recent years this process has accelerated with the decrease in the cost of sensors and communication infrastructure as well as an increasing willingness towards atomisation in society at large. Within the world of urban drainage this implies that it is now becoming possible for a reasonable price to get a real time overview of the distribution of water throughout the systems as well as performing regular automated video inspections to improve the asset data base. This will make it possible to plan, monitor and control to an extent we have not been accustomed to, with the potential of great improvements. Within the near future, the digitalisation urban drainage system will start to interact with the energy systems, driving by the mega-driver of reducing man’s overall CO_2 emissions. Pumping operations in the urban drainage systems and at the treatment plants are using substantial amounts of electricity. Much of this pumping can be displaced in time without large consequences and this flexibility can be worth a lot for electricity providers that struggle to provide stable power supply in systems with an ever-increasing share of fluctuating power producers like share of windmills and solar cells. Heat pumps that extracts heat from the wastewater will also begin to emerge, which will turn the drainage system into an energy provider which will entail new technical and regulatory challenges. Digitalisation of course does not solely affect the urban drainage community, it is rather a development which helps to bridge our community with many other communities within IWA, such as the SGs on Modelling and Integrated Assessment, Hydroinformatics, Instrumentation, Control and Automation, and Strategic Asset Management and outside IWA.

Transitions in urban drainage

Decision makers for urban drainage systems are required to decide on a daily basis how to direct their investments. The three developments discussed before, asset management, urban water management and wastewater management, may each require a different approach in the rehabilitation of sewer

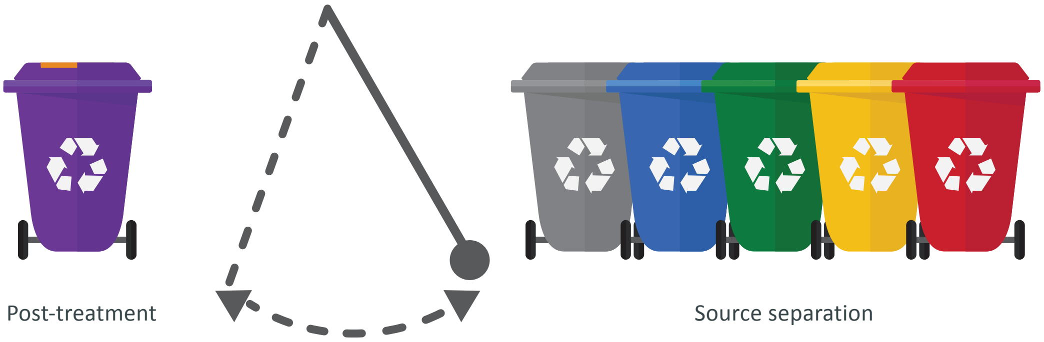

Figure 3.10 Post-treatment versus source separation

and drainage systems. The long service life of urban drainage systems make it hard to quickly adopt to new concepts and strategies in existing urban areas.

In our field, research often focuses on one of the three main developments, each of them having their own specialist groups, working groups, workshops, conferences and journals. This is necessary to progress knowledge and to develop new concepts. However, the value of an integrative approach in addressing the increasingly urgent need to transition towards more sustainable approaches to dealing with stormwater, groundwater and wastewater is increasingly recognised by urban drainage researchers. The co-development of new knowledge (both across the disciplines and in partnership with practitioners) can facilitate its uptake into practice. Further, integrative working practices facilitate the exploitation of opportunities to contribute to multiple objectives, with respect to public health, liveability of cities, climate proofing and resource recovery. With increasing awareness of the impacts of a rapidly changing climate, and the need to identify and implement multiple benefit urban drainage strategies and technologies is a JCUD research priority.

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| 3.9 |

Water in ancient civilisations

Topics and challenges on water history with emphasis on sustainability, water, health, resources recovery, and circular economy

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Introduction

The history of water is equivalent to the history of the world and the history of water quality is equivalent to the history of life.

Societies in antiquity studied, analysed and interpreted natural phenomena in an excellent way. Most of the early prehistoric civilisations flourished in plains close to rivers, where water for drinking and agricultural development was readily available (e.g., Mesopotamians near the rivers Tigris and Euphrates in Asia, Egyptians near the Nile in Africa, Hindus near Indus River, and Chinese civilisations near the Yellow and Yangtze Rivers). Following the dry period, probably in the 6th millennium BC (Fahlbusch, 2007), prehistoric societies were well established in the valleys of the rivers Nile, Indus, Euphrates-Tigris and the Yellow River. The fact that water is the basic precondition for life, motivated people to settle in places with available water to meet their water demand. As the survival of the population and thus the daily life of the people depended on water resources, it is understandable that these civilisations were highly experienced in water transfer and irrigation practices. For example, they developed sustainable aqueducts both above and underground, some of which are still in use.

In contrast, with the exception of the Minyan culture at Gla, by the Lake Kopais in central Greece, the majority of the earliest Greek societies avoided the establishment of their major urban cities close to rivers, lakes, or rich springs (Krasilnikoff and Angelakis, 2019). The observation of the locations of these centers suggests that the Ancient Greeks chose to establish most of them in the driest areas. The exact reasons for this are not clear, but we may assume that ancient Greeks of the prehistoric periods considered dry climates more convenient or healthier; ostensibly, this choice offered good protection from floods and water-related diseases (Koutsoyiannis et al. 2008). A survey from Crouch suggests, however, that an alternative to establish cities in locations close to major water courses was to choose regions with water-rich karst formations. Although Crouch's focus was on the development of Classical Greek urban centers, much support the idea that this logic can be applied to Bronze Age societies as well (Krasilnikoff and Angelakis, 2019). The implication of this is that from an early date, underground or alternatively storage of water became the solution to societal developments in the driest Southeastern regions of Greece and the Aegean Islands.

With the increasing worldwide awareness of the importance of the water resources management history, the IWA SG on WAC (Water in Ancient Civilisations) was established in 2005 and lastly the International Water Association (IWA)/International Water History Association (IWHA) SG on Water in Ancient Civilisations, abbreviated as IWA/IWHA SG on WAC was established in 2020. So far, nine IWA International and Regional Symposia and Workshops, on Water Technologies in Ancient Civilisations have been organised in several places of the world. Since the end of 2020, the Group has planned two events. In addition, the more than thousand members of the group have published numerous publications relevant to water history in the international journals.

Through activities, we support research of water heritage and preserves of ancient water systems and structures, thus expanding knowledge and understanding of the historical aspects of the development of the profession and the importance of water system heritage to the society. Through our activities, we introduce local and wider public to water heritage and thus contributes to the development of tourism and local economies. Thus, Joint IWA/IWHA-SG on WAC contributes and disseminates state of the art water history research to regional and worldwide social and economic developments.

Existing knowledge on SG topics

It is generally accepted that water, food, and energy resources have always been crucial for sustainable development of human life in urban and rural regions alike. The relationship between what nature had to offer and population demands determined livelihood standard. The availability of sufficient amounts of safe water has been of paramount importance throughout human history. Water availability determines the size of cities. Water deficiency can destroy cities and their population, and so can excessive, causing floods, erosion and disease. Numerous examples from all continent's points to this as an endemic and erratic challenge throughout history. Man, always strives to manage water resources to strengthen sustainability and to avoid one of the potentially most destructive forces of nature.

Moreover, internal relations in the local natural and socio-economic systems challenged development of sustainable water infrastructure and systems, possible solutions and thus limits the resilience of cities (Crouch, 1993). Water and sanitation infrastructures serve, as preconditions for livelihoods, but the security of livelihood capitals are vulnerable to external factors including environmental and political stresses. The significant changes of water availability in some societies was generated by political and natural stresses, and especially the role of climate changes and/or climatic variability has been crucial, much like today. Ancient water infrastructures have witnessed events and changes in the past as they have always shared the fate of cities and their populations. By studying ancient infrastructure systems, the sequence of events and possible solutions of water related problems can be understood (Mays, 2010).

To determine the various factors and features of ancient water infrastructures and systems, it is necessary to study how the development of sustainable livelihood and environmental security. Such an approach provides a means of linking socioeconomic and environmental concerns, and sound scientific analysis of short- and long-term climatic developments and other events of both types. Therefore, a multidisciplinary approach and better cooperation among relevant scientific disciplines are required, e.g., water engineers, historians, archeologists, and environmentalists. This cooperation is still not satisfactory, because there is a lack of good communication and exchange of information among professionals. Better cooperation would better define and present state of the art knowledge as well as new research, and thus be of potential use to solve current problems related to sustainable social development and climate change and to strengthen resilience of all parties involved.

Many of the world's historical cities still enclose ingenious water heritage, depicting how they in the course of time invested and adapted to local water resources, water bodies and its related hazards over time and space (Angelakis et al, 2014; Stoyle, 2014). Both continental and coastal cities proceeded with this paradigm by considering water issues while selecting locations and designing urban growth patterns. Much has been written about past water infrastructures, facilities and organisational measures, which proved to hold degree of sustainable; and in addition, efficient, equitable and ecological (Mikkonen, 2018). There is an increasing interest for exploring potentialities of that specific heritage in coping with current challenging urban water issues, likely about to become more critical with regard to observed and projected effects of climate change (UN-Habitat, 2019). Now, little is known about complex interactions between development of social organisation and water systems and how they progressed and varied across space and time. A relevant research topic would be to better understand how the water strategy (freshwater supply, wastewater management, water related hazards coping strategy) did accompany city founding and its initial development, and which role it played for urban population growth. Such research questions might be based on case studies approach, considering historical cities in various bioregions (different hydro-climatic contexts).

Besides, while water resources become either quantitatively or qualitatively less available due to the impact of climate variability and human pressure, cities deal with water shortage by overexploiting local and regional resources and/or intensifying the production of both conventional and non-conventional resources (UN-Water, 2018). Hence, cities double their vulnerability regarding availability, quality and related risks. Insofar, such strategies is mainly based on structural measures; it may have negative effects on the natural environment possibly resulting in an endless cycle of cascading effects engaging human and natural environments into a non-linear change reality that can be difficult to monitor a posteriori (UNDRR, 2019). Now studies show that past water management systems succeeded in mixing and adapting technology, jurisprudence and land use regulations, enabling cities to master and thus avoid such unsustainable situation (Aroua, 2014; Faiz, 2005). A relevant research topic would be to explore past water management as a social system possibly able to help prevent unpredictable and potentially irreversible consequences of human pressures on waterscape, dynamic and quality.

General trends and challenges

Traditionally, knowledge of how to manage water resources incorporates innovation in a dynamic fashion, subject to long-term testing, and thus achieving local and environmental sustainability. Many of the old water techniques are more valuable than the present conventional ones (Angelakis et al., 2016). Current-day engineers typically use a design period of structures with an operative horizon of about 40 to 50 years, which is related to economic considerations. Sustainability, as a design principle, has entered the engineering lexicon only within the last decade, and it is difficult to infer the design principles of ancient engineers. Nevertheless, it is notable that several ancient works have been operating for very long periods, some even until contemporary times. For example:

(a) The Peisistratean aqueduct, which was probably built in the decade from 540 to 530 BC, transported water from the foothills of mount Hymettos, to the center of Athens near the Acropolis (Koutsoyiannis et al. 2008).

(b) The Falaj (qanat) Ain Al-Aouar or falaj Al-Aouar, is located upstream at the mountain Al-Jabal Al-Akhdhar of the Al-Hajar chain, in the north of Wilayat Nizwa in Oman. It draws water from the spring of Ain Al-Aouar, which means in Arabic "the source of the blind man", or probably "the eye of the blind man" (Megdiche-Kharrat, 2018).

(c) Another most common example are the drainage systems of ancient theatres, which in some cases are still nowadays in operation mainly due to the management of the rainwater and storm water in a sustainable way (Figure 3.11a). Moreover, in some cases techniques for rainwater harvesting and reuse were developed. The collected water was either stored in nearby cisterns, as the arched cistern (Figure 3.11b) in the island Delos, Greece (Mays et al., 2013), or distributed to nearby workshops, which needed water for their operation, as in Dionysus theatre of Athens (Kollyropoulos et al., 2015).

Traditionally, water reuse, mainly for land application and irrigation, has evolved into a myriad of applications. As in historical times, the modern practice of water reuse has been developed through observation, necessity, and opportunity. The growth of megacities has highlighted the traditional concept of not using only one water and wastewater treatment plant (Angelakis et al., 2018). Today, fully centralised water and wastewater management, consisting of only one central system, appears to be untenable because it limits reuse applications. Today, decentralisation is a necessity, which corresponds to the situation in the past. Hence, lessons from past and present demonstrate that decentralisation leads to the rise of many more opportunities for local water reuse. "New technologies" that are now being implemented as well as those under development will usher in a new way in conventional and advanced wastewater treatment, with potable water reuse now representing one of the last frontiers. Then, archaeological, historical and technical evidences indicate: (a) an advanced level of water engineering and management practices in ancient times and (b) similarities in principles of present technologies with the past ones (Koutsoyiannis et al., 2008; Mays, 2010).

Ancient water systems and structures are important elements, which many countries can offer to tourists. Many tourists visit these sites and get acquainted with water heritage, their technical characteristics and the environment in which they are built and evolved. Rapid and significant changes in the society and environment affect the sustainability and even survival of ancient water and sanitation systems and their structures. That is why the topic of climate change affects ancient water and sanitation systems and structures, and this is why vulnerability and adaptation planning is one of the research priorities (Reiman, 2018). Similar applies to land change impacts, such as urbanisation, landscape modifications, and coast modifications.

Environmental livelihood security, water and sanitation systems (physical livelihood capital), integration of past practices, experiences and future challenges is also an important topic that will need to be explored. Integrating sustainable livelihoods with water-energy-food nexus requires identification of the inter-linkages between these commodities, as well as the assets of human populations and the natural environment. The dynamics of the water-energy-food nexus and the effects of the three components on water and sanitation systems need to be investigated. This means exploring resource recovery and the circular economy aspects of ancient water and sanitation systems and assessing possible adaptations to ongoing needs and policies (Bond et al., 2013).

It is well known that ancient systems were mainly “green” (carbon dioxide free) because they based their activity solely on renewable energy sources. Those old facilities were exclusively made of natural materials that have not adversely affected water and the environment. In addition, ancient water systems were characterised by very low system entropy and long lifespan/operation. To achieve this, appropriate solutions, techniques and materials have been used, which can be used with adequate customisation in present and future green-sustainable cities and communities with the same results. Therefore, a comprehensive and systematic study of the sustainability of ancient water systems is essential and may help in achievement of UN Sustainable Development Goals (UN, 2018).

Conclusions

The mentioned paradigms demonstrate that water related problems were managed effectively and responsibly ever since prehistoric times. Up to now, no new water management technologies and principles have been developed since the beginning of recorded history. In addition, the development of water technology commenced thousand years before water sciences developed in Miletus’ Ionian School around 600 BC, in Omakoeion School Croton in southern Italy by Pythagoras (ca. 570–495 BC) an Ionian Greek philosopher and the eponymous founder of Pythagoreanism, and in Athens Platonic Academy in 387 BC. Thereafter, many of the principles of hydro-technologies discovered by previous thinkers were adapted and reformulated by members of the Peripatetic School of Aristotle (384–328 BC) whose theories were also influenced by the Ionians and the rise of Neopythagoreanism. Finally, Alexander the Great (346–323 BC) founded Alexandria including the Museum and the Great Library. From the technological point of view, these paradigms manifest a very high level of technological knowledge, which must have been

Figure 3.11 Theatre in which rainwater drainage and harvesting for reuse: (a) the theatre in Delos island Island and (b) the cistern used for harvesting the drainage water.

the result of a gradual and lengthy development process (Fahlbusch, 2007). However, it is not known when, and under which conditions, this process started. Some valuable literature exists in different languages worldwide from various countries and historical eras. It is worth gathering that tremendous knowledge related to water and transfer it into concrete guidance for the purpose of restoring, adapting or creating urban water systems in line with the current Sustainable Development Goals.

By studying the conditions and processes that influenced the development of ancient water systems as well as their operation and management, it is possible to gain knowledge for future technological advances. The knowledge and principles on which ancient water systems were planned and managed can help us better define strategies, adaptation measures and strengthen resilience related to climate change and variability. The joint IWA/IWHA-SG on WAC will continue to work on identifying, preserving and disseminating knowledge of ancient water systems and structures applying available state of the art technology. Application of integrated approaches is essential in order to gain complete insight into ancient water security issues and role of water in human evolution (UNEP, 2007).

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| 3.10 |

Water reuse

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Introduction

A growing population across the globe is causing strain on essential natural resources for many sectors of the economy including forestry, energy, transportation, agriculture, and water management. To counteract this challenge, innovative strategies to reduce, reuse, and repurpose necessary resources are gaining momentum. Keeping resources in use for as long as possible, extracting the maximum value from them while in use, and regenerating products at the end of the service life is known as a circular economy.

With water needs increasing world-wide and climate variability impacting traditional rainfall patterns, it is essential that the water industry embrace the implementation of the circular economy for water. Expansive use of beneficial reuse will accomplish this goal. By treating the water to different quality standards based on the requirements of end users, known as fit-for-purpose treatment, it can be used for landscape and agricultural irrigation, toilet flushing, industrial cooling, groundwater recharge, drinking water augmentation. Similarly, resource recovery in water treatment can be used to recover nutrients such as phosphorus and nitrogen and provide renewable energy. Recovery and use of these resources provide financial advantages to water utilities and reduces the need to extract from the environment. Germany is a leader in phosphorus recovery and many other countries in Europe are expected to follow (Daigger et al., 2019). This results in increased public acceptance surrounding beneficial management of byproducts of water and used water treatment leading to resource recovery and water reuse.

Key terminology

Water reuse, beneficial use, distributed reuse systems, onsite reuse, fit-for-purpose, circular economy, resource recovery, potable reuse, non-potable reuse, agricultural reuse, industrial reuse, public engagement, used water, drinking water augmentation, surface water augmentation, groundwater augmentation.

Existing knowledge

In 2015, the United Nations (U.N.) established the Sustainable Development Goals (SDGs) [1] to help all communities in the world move toward sustainability by 2030. Responsible water management practices are essential to the success of each of the SDGs, either directly or as a foundation necessary for community advancement. The 2017 edition of the U.N. World Water Development Report, entitled “Wastewater: The Untapped Resource”, demonstrates how improved used water management generates social, environmental, and economic benefits essential for sustainable development and the importance of achieving the 2030 Agenda for Sustainable Development [2].

Water reuse can provide a reliable source of water to increase resiliency of communities and decrease dependency on freshwater sources. Water reuse has been practiced for decades; however, it is still gaining momentum in many areas which is why the SDGs can play an important role in helping bring awareness to water’s circular economy.

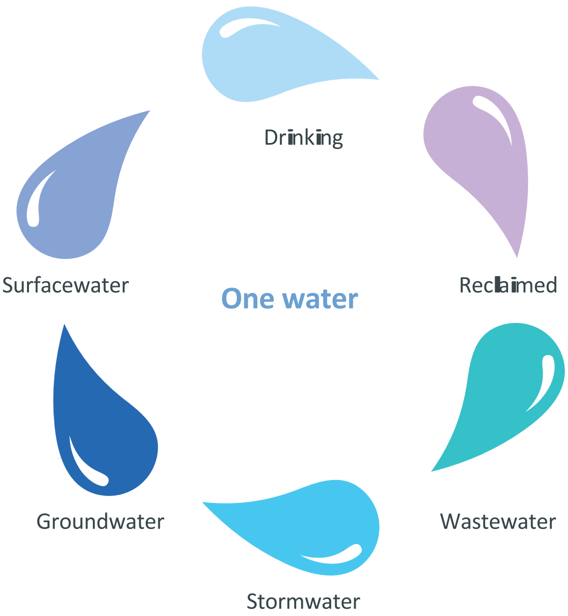
The continued need for resilient water supplies led the United States (U.S.) Environmental Protection Agency (EPA) to draft the Water Reuse Action Plan (WRAP) [3] in 2019 which identifies drivers, opportunities, and challenges for water reuse in the U.S. as well as research needs to address those challenges. Although historically permitted at the state-level, the WRAP is a federal document that proposes collaborative action to support implementation of water reuse in the U.S. Similarly, the European Commission presented the circular economy package in 2015 which committed to develop actions to promote uptake of water reuse at the European Union level [4]. This plan integrates reuse in water planning, establish minimum water quality requirements for end uses of recycled water, investigate the potential for water reuse in industrial activities, and continue research and innovation in water reuse. Minimum requirements for water reuse regulations for agricultural irrigation were adopted in 2020 within the European Union [5].

Water-stressed areas such as the southwestern U.S. must augment their drinking water source with alternative waters to satisfy projected demands. Groundwater replenishment is an attractive alternative which involves infiltration or injection of reclaimed water into temporary underground storage. Other countries including Australia, Singapore, Spain, Italy, Germany, Sweden, and Belgium are also practicing water reuse. The Water Corporation of Western Australia is the country's first full-scale groundwater replenishment system. Located in Perth, it was built to treat effluent from a nearby plant using advanced purification technologies and use the product water for aquifer recharge. Singapore Public Utilities Board (PUB) produces high quality reuse water, branded NEWater. Singapore PUB uses a multi-barrier process to create NEWater that exceeds potable reuse standards set by the U.S. EPA and the World Health Organization. NEWater will meet up to 55% of the country's water demand by 2060[6]. IWVA in Belgium features the Torreele facility Wulpen, which reuses municipal effluent for groundwater recharge in St Andre[7]. The aquifer is used for groundwater extraction to produce potable water for nearby communities while helping to prevent seawater intrusion[8]. In Sweden, the first direct potable reuse (DPR) project was established on Mörbylånga to provide an alternative to pumping water to the island and depleting the declining fresh groundwater supply. Here a blend of desalinated brackish groundwater and reclaimed water is used for drinking water supply[9]. In addition, different types of water reuse are currently utilised in nearly all countries around the world.

General trends and challenges

One water paradigm shift

Embracing the concept of circular economy resulted in a paradigm shift surrounding how we think about waste. Materials traditionally considered waste – i.e., used water, plastics, paper, and glass – are now considered valuable resources for innovative purposes. In the water industry, there has been a shift from using the term 'wastewater treatment plants' to 'water resource recovery facilities,' to focus on the products and benefits of used water treatment rather than disposal[10]. The City of Dubuque, Iowa, U.S. wastewater treatment plant shifted to a water and resource recovery center incorporating biogas recovery for digester heating and power generation[11]. Formerly known as Monterey Regional Water Pollution Control Agency in California, U.S., Monterey OneWater now focuses on the value of all types of water to meet the needs of their member agencies. The name change signifies an evolving water industry that embodies the ideals of circular economy and environmental preservation.



Distributed reuse systems

The West Basin Municipal Water District in California, USA, treats reclaimed water to five different levels dictated by regulatory permits or obligations to customers. Deemed 'designer water[12]', West Basin tailors the water quality to the end use, preventing loss of energy and cost due to overtreatment. The idea of 'designer water' led to an increased interest in distributed systems, particularly fit-for-purpose treatment facilities than can be located adjacent to specific uses or customers.

California Senate Bill 918 became law in 2010 and required the Department of Public Health to investigate the feasibility of developing criteria for direct potable reuse (DPR) in the State of California, U.S., to mitigate severe drought. In 2012, officials in San Francisco, California, passed an onsite water reuse ordinance which requires all large-scale new building construction to feature onsite non-potable reuse water

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1 https://www.un.org/sustainabledevelopment/sustainable-development-goals/
2 http://www.unesco.org/new/en/natural-sciences/environment/water/wwap/wwdr/2017-wastewater-theuntapped-resource/
3 https://www.epa.gov/sites/production/files/2019-09/documents/water-reuse-action-plan-draft-2019.pdf
4 https://ec.europa.eu/environment/water/reuse-actions.htm
5 https://ec.europa.eu/environment/water/reuse.htm
6 https://ec.europa.eu/environment/water/reuse.htm
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8 http://demoware.ctm.com.es/en/demo-sites/torreele/torreele
9 https://www.bjorneman.se/news/2019/10/28/inauguration-of-pioneering-water-treatment-plant-inmrbylnga-sweden
10 https://news.wef.org/changing-the-terms/
11 https://www.tpomag.com/editorial/2015/06/dubuque_resource_recovery_facility_keeps_it_sustainable
12 https://www.westbasin.org/water-supplies-recycledwater/water-quality

systems for toilet flushing and irrigation demands of the building. San Francisco Public Utilities Commission's Living Machine – an engineered wetland system located in the building's sidewalks and lobby – treats the building's used water and distributes it for toilet flushing. The system recycles 19 m^3 of water each weekday. This practice, known as onsite non-potable water reuse, reduces the strain on potable supplies from 45 L/day per person to 2 L/day per person by using the reuse water for uses that do not require drinking water quality standards.

Bairds Malt, a malt supplier in the United Kingdom, utilises water reuse at their facility in Witham[13]. The used process water that would ordinarily be discarded undergoes advanced treatment to produce water of potable quality. The recycled water is then used in the malting process.

Japan has incorporated water reuse since the late 1970s due to extreme water scarcity driven by exponential population growth (Ryan, 2016). Recycled water in Japan is treated to meet quality standards for non-potable purposes such as irrigation and industrial applications.

While not all utilities use the term 'designer water', there are two main varieties of water reuse in practice across the globe:

- potable reuse;
- non-potable reuse, including agricultural reuse and Industrial reuse.

Potable reuse, the process of treating reclaimed water to drinking water standards, can be divided into three subtypes. Many communities around the world utilise drinking water source that is comprised in part of used water from upstream communities, also known as *de facto* potable water reuse. *De facto* reuse is widespread across the world. A recent study quantified the degree of wastewater discharge to streams in Germany and highlighted a significant degree of impact for many drinking water abstractions via riverbank filtration[14]. The second type includes the use of an environmental buffer between the reclaimed water treatment process and the drinking water treatment process, such as discharge into a reservoir or groundwater injection. Depending on what type of waterbody is used, this practice of indirect potable reuse is known as surface water augmentation and/or groundwater recharge. This type of planned reuse has been practiced around the world for decades. The largest indirect potable reuse facility worldwide is the groundwater replenishment system operated by the Orange County water district in Southern California. Hampton roads sanitation district in Virginia, U.S., launched the sustainable water initiative for tomorrow (SWIFT). SWIFT takes highly treated water that would otherwise be discharged into nearby rivers and uses advanced water treatment to meet drinking water quality standards[15]. The water is then added to the Potomac Aquifer, the primary source of groundwater for eastern Virginia.

Direct potable reuse involves augmenting drinking water with highly treated reclaimed water directly into the drinking water distribution system or the raw water supply of a conventional drinking water plant. The New Goreangab Water Reclamation Plant (NGWRP) in Windhoek, Namibia, Africa, is the first and longest running direct potable reuse facility in the world. NGWRP, in operation since 2002, uses domestic secondary effluent as source water. In an advanced multiple barrier system, high-quality drinking water is produced and directly pumped to the drinking water network where it is blended with treated dam and groundwater. From 1968 to 2002, the Old Goreangab Water Reclamation Plant was operated using a conventional process (without ozone or membranes). Since 1968, the plant has provided approximately 35% of the overall drinking water for the city[16] without any health-related issues which could have been attributed to the use of reclaimed water. The Goreangab Plant, with over 50 years of successful practice, represents a model for water reuse projects around the world.

While most systems depend on an environmental buffer to blend highly purified reclaimed water with native waters, at least three U.S. communities (Cloudcroft, New Mexico, Big Springs, Texas, and Wichita Falls, Texas) are developing drinking water augmentation systems without the use of a natural buffer.

Because agriculture is typically the number one water globally, agricultural water reuse for irrigation of food crops is gaining momentum. Agricultural water reuse provides additional benefits such as decreased need for fertilisers due to elevated nutrient content in recycled water (Sheikh et al., 2019). Israel has used recycled water for agricultural irrigation since the 1970s and currently recycles approximately 90% of its used water[17]. Spain reuses 20% of its water and applies approximately 70% for agriculture. OceanMist Farms in California, U.S., uses recycled water for farming operations, which has reduced use of potable water for irrigation and decreased seawater intrusion by reducing strain on well water[18].

Urban non-potable reuse utilises reclaimed water for non-drinking beneficial uses such as landscape and golf course irrigation, toilet flushing, and wetland restoration. It can also be used in industrial settings for cooling towers, boiler cooling, cleaning, and processing. While not as common as the other types of non-potable water reuse, industrial water reuse is

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[13] http://www.bairds-malt.co.uk/Bairds-Malt/About/safetyhealth-environment

[14] https://pubs.acs.org/doi/10.1021/acs.est.8b07216

[15] http://swiftva.com/

[16] http://legacywater360.server309.com/wp-content/uploads/2015/07/WQ-Case-Study-4-Windhoek-Namibia-100815.pdf

[17] http://conservewaterforfood.org/water-reuse-inagriculture

[18] https://www.oceanmist.com/natural-resources

beneficial to companies looking to reduce their expenses for freshwater supplies, environmental footprint and adopt sustainable business practices. The potential for increased industrial reuse exists worldwide. In the U.S., approximately 75% of all existing and proposed power plants are within 10 miles of a municipal used water treatment facility. Despite the potential, only about 60 of 5,000 U.S. power plants currently use municipal recycled water for industrial applications [19].

Public perception

Effectively engaging policy makers, researchers, technology providers, and the public is a key element of all successful water projects. The way in which a novel treatment process or technology is communicated to stakeholders affects the overall chances of implementation. In the U.S., the topic of potable water reuse is particularly dependent on public acceptance, as reuse is still perceived as a foreign concept in many areas of the country. Monikers in the media such as 'toilet to tap' have negatively affected public opinion of water reuse, while targeted community engagement efforts by utilities such as Orange County Water District, City of San Diego, PureWater Monterey, and others have increased public support. Information based on sound-science, thoughtful messaging, and an accessible venue for stakeholders to connect are needed to make innovative solutions to the nation's water issues more widespread. This can be accomplished through educational programs in schools, outreach programs at utilities, public workshops, and marketing campaigns to disseminate important information surrounding water reuse and resource recovery. Given the popularity of the circular economy of traditional recyclables, it is essential for the water industry to embrace these lessons and begin messaging to the public on their greater responsibility to sustainable practices.

Conclusions and future research

As the momentum of water reuse grows, high-quality research based on sound science is needed to provide utilities with accurate, up-to-date information to inform their decision-making processes. Organisations across the globe are conducting major innovative water reuse research programs including the Global Water Research Coalition (Australia), The Water Research Foundation (U.S.), KWR (Netherlands), the Federal Ministry of Education and Research (BMBF) in Germany, and the Water Research Institute of the Italian National Research Council (Italy). Associations such as the International Water Association, Water Services Authority of Australia, and WateReuse Association provide access to educational materials and advocacy opportunities to advance water reuse. Many utilities in the U.S. are funding water reuse research programs, such as Upper Occoquan Service Authority (Virginia), Orange County Water District (California), and Hampton Roads Sanitation District (Virginia). Gwinnett County Department of Water Resources in Georgia, U.S., created 'The Water Tower', a nonprofit organisation addressing water-related research and technology needs. Trending water reuse research topics include improving source water protection, treatment process optimisation, public health, and environmental protection, increasing water quality, addressing regulatory barriers, nutrient removal and recovery, and enhancing public engagement. While not an extensive list, these organisations are providing the research and materials needed to make water reuse prevalent across the globe.

Each of the U.N.'s SDGs for 2030 includes an element of water and provides a great opportunity for water reuse to play an integral role in the future of our planet. Feasibility studies can provide communities with the important information needed for decision making surrounding incorporating reuse as part of a diverse water portfolio. For example, the Kingdom of Saudi Arabia relies heavily on seawater desalination to meet increasing freshwater demand. However, with under 10% of the municipal used water generated currently being reused, Saudi Arabia is projected as the third largest reuse market after China and the USA (Drewes et al., 2012).

Successful water reuse projects can serve as functional examples to aid in the development of new improvements to existing reuse programs. The 2019 report published by Water Research Australia titled "Potable Water Reuse – What can Australia Learn from Global Experience? (Khan et al., 2019)" stresses the importance of any jurisdiction considering a potable reuse project to educate themselves and understand global experiences. The successes and challenges of other utilities establishing reuse programs can provide regulatory, engineering, and engagement insights that could make or break a project. The Region of Murcia, part of the most water-stressed district in Spain, uses recycled water in agriculture (Navarro, 2018). Agriculture is a key part of the economy and as a result, the region has made major strides in responsible water management. A monitoring agency was established to create treatment plans for reuse and a 'sanitation fee' tax was implemented to help cover the operating costs of water plants in the region.

An international network of communication among water and used water utilities would allow for easy information exchange for those considering water reuse. For example, the department of Vendee Eau in France is considering a surface water augmentation indirect potable reuse scheme to offset seasonal peak demand water scarcity [20]. The reuse facility would supply the Jaunay Reservoir, the drinking water supply for the surrounding area, with treated municipal effluent. A preliminary demonstration project is underway to determine the appropriate treatment train and address health and public acceptance concerns.

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[19] https://watereuse.org/event/multipurpose-water-reusein-the-power-sector-an-investigation-at-an-electric-utilityand-wetland-in-florida/

[20] http://demoware.ctm.com.es/en/demo-sites/vendeeeau/vendee-eau

Though challenges to the implementation of water reuse projects such as public perception, cost, regulatory barriers still exist, a wider circular economy perspective could address these issues more effectively and provide better context for the need for water reuse [21]. Working together to develop best management practices will help propel the water reuse industry forward toward a safe, sustainable, and reliable water supply.

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Pre-treatment of industrial wastewaters

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Introduction

Industrial wastewater is a global issue and covers a wide range of industries ranging from the food and beverage industries (representing organic wastes) through to petrochemical, pharmaceutical, mining and electroplating industries, discharging (by their nature) a significant variety of contaminants. The quantity of wastewater produced and its overall pollution load are continuously increasing worldwide. Over 80% of the world's wastewater is released to the environment without proper treatment, discharged illegally to either sewer or environment, resulting in a number of significant problems (environmental degradation, biodiversity deterioration, uptake into the food chain, etc.).

As a general rule, the locality of industries dictates, to a large extent, the discharge of generated wastewaters. Many large industries are located in metropolitan or outer urban areas, and most of these will generally discharge to an available sewer, which transfers the waste to a municipal wastewater treatment plant. However, there are a large number of facilities that are located in regional and rural areas (dependent on resources used for the industry). These will include mine sites, but may also include wineries, abattoirs and similar facilities, which rely on food production. In these cases, it is more common that wastewater is treated on-site and discharged to the environment. There are also a number of centralised industrial treatment facilities which wither have a small sewer catchment dedicated to the industrial discharge (common in Southeast Asia) or rely on tanker transport (common in the Middle East).

Industrial wastewater is typically characterised by a wide range of contaminants which if released inappropriately to the environment will impact on water resources and local amenities. In the last 30 years, evidence of industrial contamination has prompted for calls on tighter regulations of these systems, and wastewater has become a key target for control by regulatory authorities. Coupled with this, in some areas, where drought or water resources are scarce, the wastewater is regarded as resource, and treatment and reuse of the effluent is advocated. Consequently, a key focus in many developed countries is the appropriate and sustainable treatment of industrial wastes, to enable safe discharge to sewerage systems or the environment and recovery of by-products. About 25% of greenhouses gas are generated by industrial facilities which now are called to contribute to the reduction of emission, introducing green processing and recovering valuable compounds from wastewater and sludge. According to the United Nations World Water Development Report (2017 edition), improved wastewater management generates social, environmental and economic benefits, and is essential to achieving the 2030 Agenda for Sustainable Development Goals. Wastewater is poised to play a critical role in the context of a circular economy, whereby economic development is balanced with the protection of natural resources and environmental sustainability, and where a cleaner and more sustainable economy has a positive effect on the water quality.

There is a significant amount of research associated with control of industrial wastewaters. Much has also been undertaken on anaerobic treatment of high organic wastewaters to biogas, and waste to energy. The sludge has been used for composting or fertilisation. New processes and technologies are under development based on biorefinery concept. This represents a major driving force in development and take-up, on the side of the traditional ones, of new pre-treatment technologies of industrial wastewaters, where economic gain may be realised in treatment of wastewater, through renewable energy generation, special compounds recovery, enhanced biodegradation in post-treatment, etc.

Some aspects of the industrial wastewater pretreatment programs (technical, administrative, fiscal) include the impact of industrial discharges on municipal treatment works and transfer systems; characterisation and categorisation of industrial wastewaters; end of pipe treatment technologies and in-plant water efficiency control, planning, development, management and troubleshooting of industrial wastewater treatment facilities; recycling, material recovery and waste minimisation; waste to energy and treatment and disposal of toxic sludge.

Consequently, a robust approach in pre-treatment of wastewater systems from an environmental and economic base, targets generation of useful by-products:

- renewable energy generation that mitigates CO_2 and CH_4 emissions;
- effluent re-use, especially in areas of water scarcity;
- residuals management and post-treatment;
- recovery of by-products and special compounds;
- green processing.

Current issues

Industrial wastewater is typically characterised by a wide range of contaminants which if released inappropriately to the environment will create an impact on local and potentially regional resources (surface water, groundwater and land). This in turn, can adversely impact on natural amenities and human habitation (drinking water, crop growth, food chain, etc.). Consequently, the appropriate collection, treatment and disposal of contaminants of concern, is paramount to ensure sustainable industrial operations and management.

Contamination from industrial wastewater includes the following:

- organic overloading of surface waters, leading to loss of amenity;
- discharge of persistent substances impacting the biota in natural water bodies;
- loss of nutrients and eutrophication in surface water;
- emission of greenhouse gases as part of inadequate/ storage and treatment of high strength organic wastes;
- impacting of beneficial re-use on municipal biosolids (through adsorption of heavy metals and toxic materials);
- mine acid drainage;
- arsenic groundwater contamination;
- land contamination.

Around the world, there are numerous cases of industrial scale contamination and losses of environmental and social amenities from legacy pollution (mine sites in South America, South Pacific, Africa, eastern Europe, etc., industrial pollution and contamination of potable drinking water supplies in Africa, the Americas, across Asia).

Cost-effective treatment is also a major issue, with many industrial operators, not interested in treatment of the wastewater unless there is a rapid payback or unless the core business is impacted, with environmental concerns often last on the business agenda. It is fair to say that most operators adopt economic principles which drive the process of wastewater management and implementation.

Legal, policy and management systems affecting industrial innovations

The UN Sustainable Development Goals (SDGs) (2017) have a significant implication on industrial, manufacturing and commercial activities, when it comes to environmental legislation both nationally and within global trade. The SDGs target global consumption of resources and production patterns, in parallel with specifically identifying socio-economic trends and desired outcomes.

Industries are being called upon to transition to new models of energy and resource efficiencies. Revising policies and legislation around the globe, will encourage industrial sectors to adopt a more resilient and sustainable outlook, based not only on economic models. Typical research and development by environmental and academic institutes could impact on the following industry aspects:

- innovation that could bring smarter systems to achieve SDGs;
- improvements in efficiencies in monitoring and control tools;
- application of applied corporate social responsibility (CSR) reporting schemes;
- planning and general audit of efficiency improvement and operation to minimise waste/wastewater streams over time to achieve SDG’s;
- waste to energy applications;
- production of biomolecules by new fermentative processes;
- use of ionic liquids for molecules recovery;
- use of graphene as an evolutionary material with potential to replace many aspects of controlling/capturing contaminants;
- sludge thermal valorisations.

Risk analysis in industrial production has matured from prevention scheme to a business evaluation model with alternatives to clean technology sought from early design, mainly in Europe and few other parts of the world. This improves sustainability aspects to the supply chain and beyond.

TABLE 3.1

INDUSTRY	TYPICAL CONTAMINANTS	TYPICAL PRE-TREATMENT
Dairy	Organics, fats [BOD 3,000 mg/L]	DAF, biological (aerobic)
Meat/poultry	Organics, fats, blood, manure [BOD 2–5,000 mg/L]	DAF, biological (anaerobic/aerobic)
Vegetable/fruit	Dissolved organics, sugars [BOD (2,000 mg/L)]	neutralisation, biological (aerobic)
Bakery	Organics [BOD 3,200 mg/L]	Biological (aerobic)
Iron/steel	Phenols, SS, ammonia, cyanide [BOD 500 mg/L]	Coagulation (biological)
Galvanising industry	Heavy metals	Chemical precipitation, filtration
Petrochemicals	Phenols, oils [BOD 750 mg/L]	Separation, chemical oxidation and biological treatment
Pulp/paper	SS, organics [BOD 4,000 mg/L]	Separation, biological
Textiles	SS, Organics, metals [BOD 6,000 mg/L]	Coagulation, biological, membrane, ozonation
Plastics/resins	Organics, phenol, oils [BOD 2,500 mg/L]	Separation, chemical oxidation and biological treatment
Beverage	Organics, sugars [BOD 2,000 mg/L]	Biological (high-rate anaerobic, aerobic)
Per- and polyfluoroalkyl substances (PFAS) wastewater streams	Organics, chlorinated slowly degradable chemicals	Ion exchange

Existing knowledge and treatment of wastewater

As a general rule, locality of the industry will dictate the discharge of the generated wastewater. The availability of the sewer typically results in preferential discharge to the sewer, with subsequent dilution with domestic wastewater and treatment affected by the municipal WWTP. There are also industries located in regional and rural areas (dependent on resources used for the industry), which typically are licensed to treat on-site with local disposal (usually more stringent license and permit criteria). Consequently, the treatment of industrial wastewaters is very site specific and the number of pre-treatment units are appropriate for these environmental permits – which are dictated by the type of contaminants and the required water quality criteria.

There are numerous technologies for treatment – e.g. dissolved air flotation (DAF), anaerobic digestion, aerobic oxidation, chemical oxidation, enzyme attack, membrane separation. Most of the processes have been developed from wastewater and water treatment fields. However, specialised technologies have also been developed, particularly to deal with some of the more noxious and recalcitrant contaminants of concern in specific industries.

Some new contaminants, such as PFAS, are now seen to encroaching on the industrial landscape with impacts in sewers and sludge materials, impacting sustainability expectations. This is increasingly becoming an issue, which affects industrial pre-treatment already.

Some examples of pre-treatment systems for varying industries in developed countries are summarised in Table 3.1.

It can be seen that DAF, biological treatment and chemical coagulation are common processes. It should, however, be acknowledged, that contaminant take up in the sludge of the treatment system will require specialist management, and the more noxious contaminants requiring chemical fixing and disposal at a secure landfill.

General trends and challenges

As noted above, the key priority for pre-treatment of industrial wastewaters is demonstration of control of contaminants and enabling sustainable operations and management of resources.

In Europe there is considered to be a renewed environmental conscience creating a shift in industrial production, use of resources and energy (use of energy efficient technologies and the introduction of renewable energy resources including solar, biomass, wind and hydro-power). Legislation and economic incentives have been introduced to encourage adoption of ecologically friendly design. Up to 1980, end-of-pipe pollution reduction was typically adopted, after which there was a strong focus on legislation. In 2000, cleaner technologies emerged, and in 2010, the advent of sustainable production has now largely been adopted in Europe.

Anaerobic digestion, bioethanol, acetic acid, lactate and hydrogen production, membranes and tri-generation are some of the most promising technologies allowing the recovery of byproducts and simultaneous production of heat, cooling and power with technical, economic and environmental benefits. However, there are numerous other technologies currently being researched and implemented, including the following:

- low energy DAF systems (smaller, more efficient, bubble size, without chemicals) to enhance performance and operating costs;
- biochemical injection materials (including reactants, catalysts, adsorbents) and nano-membranes for dealing with pesticides;
- chemical oxidation processes (including Fenton, pyrite catalysed by hydrogen dioxide, sodium hypochlorite and Ferrate oxidation) of pulp/paper industrial wastewater;
- use of adsorption materials for removal of a wide range of contaminants (including colour from textiles, heavy metals, radioactive materials);
- nutrient recovery (Phosphate precipitation, ammonia stripping etc.);
- aerobic, anaerobic and anoxic biofilm reactors.

There is also consideration to enable an increasing adoption of effluent reclamation from pre-treatment of industrial wastewaters. There are a number of installations in Australia and elsewhere that have adopted advanced treatment (at the end of the biological system) to enable reclamation for hosing down and washing (but separated from the production of food stuffs). Examples include breweries (several in the USA and Australia), fruit and vegetable processing. The latter has also incorporated on-site capture of roof water to add to the effluent reclamation water.

Conclusions and research or development agenda

In summary while industrial pretreatment covers a wide array of industries, the solutions are very site specific. General trends include research and development of the following:

- anaerobic digestion and generation of energy for high strength wastes;
- membrane treatment for entrapment of contaminants and water reuse;
- ion exchange and adsorption process for metal and PFAS contaminants;
- water efficiency and advanced treatment methods to achieve water reclamation/re-use;
- nutrients recovery; and
- new biofilm biological processes.

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