The Handbook of Environmental Chemistry

Volume 102

Founding Editor: Otto Hutzinger

Series Editors: Damià Barceló • Andrey G. Kostianoy

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ICT for Smart Water Systems: Measurements and Data Science

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Series Preface

With remarkable vision, Prof. Otto Hutzinger initiated *The Handbook of Environmental Chemistry* in 1980 and became the founding Editor-in-Chief. At that time, environmental chemistry was an emerging field, aiming at a complete description of the Earth's environment, encompassing the physical, chemical, biological, and geological transformations of chemical substances occurring on a local as well as a global scale. Environmental chemistry was intended to provide an account of the impact of man's activities on the natural environment by describing observed changes.

While a considerable amount of knowledge has been accumulated over the last four decades, as reflected in the more than 150 volumes of *The Handbook of Environmental Chemistry*, there are still many scientific and policy challenges ahead due to the complexity and interdisciplinary nature of the field. The series will therefore continue to provide compilations of current knowledge. Contributions are written by leading experts with practical experience in their fields. *The Handbook of Environmental Chemistry* grows with the increases in our scientific understanding, and provides a valuable source not only for scientists but also for environmental managers and decision-makers. Today, the series covers a broad range of environmental topics from a chemical perspective, including methodological advances in environmental analytical chemistry.

In recent years, there has been a growing tendency to include subject matter of societal relevance in the broad view of environmental chemistry. Topics include life cycle analysis, environmental management, sustainable development, and socio-economic, legal and even political problems, among others. While these topics are of great importance for the development and acceptance of *The Handbook of Environmental Chemistry*, the publisher and Editors-in-Chief have decided to keep the handbook essentially a source of information on "hard sciences" with a particular emphasis on chemistry, but also covering biology, geology, hydrology and engineering as applied to environmental sciences.

The volumes of the series are written at an advanced level, addressing the needs of both researchers and graduate students, as well as of people outside the field of "pure" chemistry, including those in industry, business, government, research establishments, and public interest groups. It would be very satisfying to see these volumes used as a basis for graduate courses in environmental chemistry. With its high standards of scientific quality and clarity, *The Handbook of Environmental Chemistry* provides a solid basis from which scientists can share their knowledge on the different aspects of environmental problems, presenting a wide spectrum of viewpoints and approaches.

The Handbook of Environmental Chemistry is available both in print and online via www.springerlink.com/content/110354/. Articles are published online as soon as they have been approved for publication. Authors, Volume Editors and Editors-in-Chief are rewarded by the broad acceptance of *The Handbook of Environmental Chemistry* by the scientific community, from whom suggestions for new topics to the Editors-in-Chief are always very welcome.

Damià Barceló
Andrey G. Kostianoy
Series Editors

Preface

The well-publicised and growing concerns about worldwide freshwater resources for human consumption impose increasing attention and focus on the monitoring, assessment, and protection of these resources. Indeed, information and communication technologies (ICT) are currently playing a key role in the observation of water systems, both for what are regarded as man-made infrastructures and for those that are regarded as being water in its natural form.

The wide context covered by ICT implies a very heterogeneous technological framework, which involves several multidisciplinary aspects, and also encompassing several application fields. Without seeking to be exhaustive, one may mention the development of new observational approaches, direct sensing techniques, sensor networking architectures, data processing and analysis methods, and integration with large data systems. These are just a few examples of the several thematic areas that can be individuated. In addition, such wide multidisciplinary coverage embraces many of today's hot topics, such as crowdsourced data collection, the internet of things (IoT), and the consequent management and analysis of big data.

Today, 'smart cities' and 'smart water networks' are cutting-edge topics in the technical literature concerning water systems. The practical objectives of smart water networks (and of digitalisation in general) are essentially driven by the demand for increased efficiency of whole systems, as a response to increased consumption scenarios, uncertain climate change, and the relating pressure on the higher quality portion of freshwater resources destined for human consumption.

The chapters of this book focus on new perspectives for the monitoring, assessment, and control of water systems, offering an updated survey of recent advances in tools and concepts originating from the ICT sector applied in the 'smart water' context. The aim of this book is to present a portrait of up-to-date observational techniques, data processing approaches, and sensing technologies for water, giving further particular attention to the implication of multiple data science aspects, e.g., data analytics, cloud computing, and machine learning.

Within this framework, the chapter by Mounce [1] investigates the opportunities offered by data science in the context of smart water utilities. He discusses the role played by digitalisation for smart water networks, analysing several aspects of IoT, artificial intelligence, cloud computing, blockchain, and other new technologies. The chapter explores relevant issues connected with data science applications to the water industry. The first obstacle to the adoption of digital technologies is related to the extraction of useful information from big datasets, being that the water industry is generally considered as 'data-rich but information poor'. Thus, collected data are typically underused and data analytics are still not generally perceived as valuable, in the road map to more efficient networks based on information and knowledge. Currently, available computing power permits the implementation of data-driven modelling and deep learning techniques for prediction and classification purposes. The author foresees strong possibilities offered by deep artificial neural networks, based on their excellent unsupervised feature extraction capabilities. Big datasets concerning water quality generated by multiparametric sensor systems are given as an example of relatively undeveloped sectors for data analytics, offering opportunities for further developments, which are discussed also in other chapters of this book [3, 5]. Finally, the chapter provides reference and overview of case studies, demonstrating the kind of applications that are candidates to be more commonplace in the near future.

As pressure increases on water resources, there is a growing emphasis for water service providers to minimise the loss from leakage. Optimal sensor placement in water distribution systems for leak/burst detection and localisation is a well-established and very productive research field. Its primary focus is to minimise the cost of a proposed sensor network infrastructure while maximising the capability to detect and localise leaks and bursts through the analysis of the collected data. Romano [2] provides a systematic review of previous work covering relevant articles published over the last decade aiming at rationalising the work carried out in this field. The chapter presents a synthesis and analysis of the relevant published works to: (1) provide insight and awareness of differing arguments, theories, and approaches; (2) highlight their capabilities and limitations; (3) identify the state of the art in their development. The chapter also provides insight and awareness of differing approaches that have been proposed to tackle specific issues encountered by researchers when developing their proposed techniques such as model and measurement uncertainties. Trends and gaps in the current research and future research directions are identified and discussed, and a number of considerations to promote further developments in this important field of research are presented. This comprehensive chapter can serve as a useful reference resource for researchers and practitioners involved in sensor network design for leak/burst detection and localisation methodologies and in the development/adoption of these techniques.

During recent decades, the role of data as a vital resource that enhances decision-making and which supports efficient systems operation has become evident, with a growing number of water supply companies viewing data as a key organisational aspect that has to be properly managed, instead of an operational side-product. At the same time, drinking water systems have increased in complexity and feature smarter elements, which in turn leads to a data-richer operational environment. Castro-Gama et al. [3] address this challenging context and the often-overlooked factor of ensuring high data quality and preventing errors in data streams. The chapter provides a bird's eye view of data validation in the drinking water industry of The Netherlands towards better data quality control policies, by providing insights on (raw) data validation in two problem types, one of water quantity and one of water quality. The chapter concentrates on a specific aspect of the overall data quality control chain, which deals with faulty data detection and isolation. Furthermore, of interest here are errors in the measurements, because sensing and human data editing processes lead to raw data distortion in the form of, e.g., drift, bias, precision degradation, or sensor failure. The focus lies on data validation to determine faulty data and the identification techniques, without expanding further on the decision-making process regarding accepting or rejecting faulty data. The authors present the results of surveys conducted with four water companies, a literature review on faulty data detection techniques, and then propose a data quality control approach using simple techniques. Case study results are presented including data validation for one water company. Best practices and issues arising from these examples regarding data quality control by water utilities are identified, as well as recommendations for future research and application of faulty detection techniques in the Dutch drinking water sector.

Monitoring wastewater has always been a challenge. Wastewater systems can vary in both size and complexity ranging from small and simple rural catchments to large and complex urban conurbations. In the wastewater collection network, historically, there has been a lack of permanent wastewater monitoring because of the propensity for fouling and the complications of monitoring both gravity and pressurised networks. In engineering and operational terms, the wastewater network has also been treated as a separate entity to the wastewater treatment works, which is, in reality, part of the same system. The wastewater treatment works tend to be much better monitored depending upon the size of the works. However, this monitoring has been very much based upon single system instrument-based control systems (e.g., a dissolved oxygen control system for an activated sludge plant). Grievson [4] presents a more holistic systematic approach, which is based upon the philosophy of the resource factory and treating the outputs from the wastewater treatment works as a product. The chapter looks at the different elements of the system as a whole and looks at the philosophy of operation that a smart system would put in place and the measurement and control needs required. The future of both the wastewater network and the wastewater treatment works will be a much more holistic approach bringing the network and the treatment works together and treating it as a single system. In this way, rather than operating the wastewater treatment system for process control with the aim of protecting the water environment, it can also be operated for resource recovery and energy efficiency with a much wider environmental benefit. This chapter provides valuable background for researchers and practitioners interested in smart wastewater networks (including opportunities and barriers) and smart wastewater treatment (including preliminary, primary/secondary treatment and sludge and resources recovery processes).

Online monitoring of several common parameters of water quality is used in water distribution systems, in order to ensure its safety for drinking and sanitation. The most common parameters are free chlorine, turbidity, and pH. A water quality event will typically result when one or more parameter values reach abnormal levels. Detection of water quality events before customers are affected is paramount to prevent possible public health impacts and potential regulatory action. Several general methods have been suggested in the past for identifying and classifying such water quality events from multiple parameters. These methods include supervised methods such as regression or regression trees and methods that make use of unsupervised learning such as clustering. The chapter by Brill [5] presents and demonstrates the utilisation of radial basis function as a tool for detection and classification of abnormal events in water quality. The methodology is based on calibration of a radial basis function using historical true events classified by human experts. The aim of the process is the selection of parameters that ensure zero false-negative events. The chapter continues to describe the main method of using radial basis function and then compares four different kernel functions, which are used for implementing the radial basis function. The case study part of the chapter illustrates actual analysis of real-world data (obtained from a monitoring station located in a large city) as well as an illustrative example (data originating from a laboratory rig). The chapter concludes with some practical advice on how kernel functions should be selected for this task and will be of value to practitioners implementing their own water quality alert systems.

The first five chapters of this book show a general portrait of the many implications of data science with the water industry, in particular for what regards specific monitoring demands and also, more in general, when dealing with big datasets of heterogeneous parameters. The potentialities and the opportunities offered by the information and communication technologies (ICTs) for improving the management of water are globally recognised. However, ICT solutions are not well exploited in developing countries and for solving this issue a partnership approach, based on open innovation, is necessary. Mvulirwenande and Wehn [6] show how ICT-focused water innovation partnerships (ICT-WIPs) can play a relevant role in building the capabilities of developing countries to implement smart water systems. In particular, this study demonstrates that ICT-WIPs allow a variety of stakeholders in the water sector (such as municipalities, ministries, large utilities, and regulatory agencies) to work together and increase the awareness about the potential of smart water systems. At the same time, the innovation partnership approach promotes the culture of mutual learning, thus allowing partners to strengthen each other's innovation competences relating to smart water systems in developing countries. This is particularly true when, as in the case of the ICT-WIPs analysed in this study, partners from foreign countries need the knowledge and experience of local partners (e.g., about specific problems concerning the water systems, existing solutions and their weaknesses, possible additional local risks). Finally, the nature of the ICT-focused water innovations analysed in this study leads to the insight that fostering smart water systems in developing countries requires to rethink not only the technologies themselves but also the business models around them.

In times of IoT and 'social sensing', also the observation of hydrological contexts may take benefit from low cost and 'pervasive' sensing systems, opening the possibility to novel approaches for capturing relevant information. In this frame, one of the main issues to solve is the availability of heterogeneous and intermittent observations. The chapter by Mazzoleni et al. [7] describes novel methods for optimally assimilating such observations into hydrological models, focusing on the particular application of flood prediction. The aim of this chapter is to explore numerical approaches for integrating crowdsourced observations from static social sensors within hydrological and hydrodynamic modelling framework to improve flood prediction. The distinctive characteristic of such heterogeneous observations is their varying lifespan and their spatial distribution, which make more complex the implementation of standard model updating techniques. This chapter applies different innovative assimilation techniques within two case studies, where synthetic flow observations are generated to represent the different intermittency and accuracy scenarios of the crowdsourced observations. It was found that crowdsourced observations can significantly improve flood prediction if integrated into hydrological and hydraulic models. Moreover, a network of low-cost static social sensors can actually complement traditional networks of static physical sensors, for the purpose of improving flood forecasting accuracy.

Precipitation is a key hydrological process in the water cycle, whose observation is increasingly required for modern water and environmental management. Conventional precipitation measurements by rain gauges cannot provide sufficient spatial and temporal coverage for many hydrological applications, such as urban drainage system modelling. Weather radar is a remote sensing instrument that has been increasingly used to estimate precipitation for a variety of hydrological and meteorological applications, including real-time flood forecasting, severe weather monitoring and warning, and short-term precipitation forecasting. Weather radar provides unique observations of precipitating systems at fine spatial and temporal resolutions. The potential benefit of using radar rainfall in hydrology is huge, but practical hydrological applications of weather radar have been limited by the inherent uncertainties and errors in radar rainfall estimates. Uncertainties in radar rainfall estimates can lead to large errors in their applications, so radar rainfall measurements must be corrected before the data are used quantitatively. Nanding and Rico-Ramirez [8] have introduced the latest advances in the measurement and forecasting of precipitation with weather radar. The common uncertainty sources include radar hardware calibration, echoes due to non-meteorological origin, attenuation, variations in the vertical profile of reflectivity, and variations of raindrop size distribution. The techniques for adjusting radar rainfall with rain gauge measurements are described. Precipitation forecasting (called 'nowcasting') using weather radar is valuable in its applications in real-time flood forecasting.

Accurate soil moisture information is critically important for hydrological applications such as water resources management and hydrological modelling. This is because soil moisture is an important element in the ecosystem and hydrological cycle, regulating evapotranspiration, precipitation infiltration, and overland flow. In contrast with in situ instruments, modern satellite remote sensing has shown a huge potential for providing soil moisture measurements at a large scale. However, its effective utilisation in the practical projects still needs comprehensive research. Zhuo [9] has introduced the advances and potential issues in the current application of satellite soil moisture observations in hydrological modelling. The key issues include soil moisture measuring methods, hydrological evaluation of satellite soil moisture, error distribution modelling of soil moisture measurements, and the need for new hydrological soil moisture product development. It has been found that hydrological application of soil moisture data requires the data relevant to hydrology. In order to meet the requirement, two important research tasks are needed: the first is to carry out comprehensive assessments of satellite soil moisture observations for hydrological modelling, not merely based on evaluations against point-based in situ measurements; the second is that a soil moisture product (e.g., soil moisture deficit) directly applicable to hydrological modelling should be developed. Only fully accomplishing these two steps will push forward the utilisation of satellite soil moisture in hydrological modelling to a greater extent.

There is an increasing demand for automatic chemometric solutions for water quality monitoring, the main requirements being their autonomous operation, low cost, and low maintenance. Today, there is a range of optical sensor technologies that are capable to perform most analytical tasks and are characterised by full solid-state, no need for reagents, and capability to withstand harsh working conditions, as it is needed when the measurement points are outside protected monitoring locations (e.g., treatment plants) and relevant parameters have to be acquired directly in the external environment. van den Broeke and Koster [10] introduce a selection of optical sensing technologies, which can provide valuable information on the quality of water. The measurement techniques that they describe are suitable for process monitoring and control applications, as well as for early-warning systems. The chapter explores the basic principles of radiative transfer at the foundation of spectroscopic methods and the fundamentals of the signal processing for the extraction of chemical information from the acquired signals. The survey of sensing methods covers the absorption spectrometry in the UV/Vis spectral region, illustrating both selective measurements of specific substances (e.g., BTEX, nitrate, and nitrite) and more generic features, like the colour, the amount of total suspended solids, and the ‘sum organic parameters’, which are recognised as excellent overall water quality indicators. The chapter also covers basic aspects and applications of fluorescence spectroscopy and infrared spectroscopy in the NIR (near-infrared) domain. Further methods, which are considered as promising and are also already marketable, are described in this survey: Raman and laser-induced breakdown spectroscopy, refractive index measurements, and image analysis. Despite the fact that optical methods are based on mature technologies that have a solid physical background, they are still not much used by the industry and still have a big potential to deliver. Optically based methods are very attractive candidates to perform automatic online field measurements, both for selective parameters, i.e., in a way equivalent to traditional analytical methods, and for overall water quality assessments, i.e., for change-detection and early warning purposes.

In addition to the online measurement of chemical parameters, the monitoring of possible organic threats to the quality of water is also of utmost importance, and technologies for the direct sensing of such contaminants based on biosensing techniques are currently under development. Della Ventura et al. [11] describe a very attractive sensing technique for the in situ monitoring of organic contaminants based on quartz crystal microbalance (QCM) devices. The chapter introduces the basic theory of QCMs, the detection scheme and its practical embodiment (the electronic interface and signal analysis) for an appropriate extraction of the needed information. The peculiarity of the proposed approach consists in the functionalisation of the QCM gold surface, obtained by immobilising a 'recognition layer' of antibodies on the surface of the crystal, which is the key aspect for the sensitivity and specificity of QCM-based immunosensors. The chapter, after introducing the theory and modelling of the QCM working mechanism, analyses the response of a quartz crystal resonator in contact with a liquid sample. Finally, the surface functionalisation and the detection scheme are discussed, with regard to particular bacteriological contaminants like Escherichia coli and pesticides like parathion. This promising sensing approach offers very high selectivity, real-time measurement capability, and high sensitivity, thanks to the fact that a QCM is capable of measuring mass changes as small as a fraction of a monolayer of atoms, as the authors report.

This book is intended for a wide audience of readers, such as postgraduates, researchers, and stakeholders at various levels. It is also intended for those experts who want to widen their purview to adjacent fields of expertise and do not necessarily have an ICT or hydroinformatics background.

Without aiming to be exhaustive, the present volume seeks to be a selective survey of novel measurement technologies and data analysis approaches for water systems.

Chapters of this book have been peer-reviewed by two reviewers per chapter. In some cases, more than one review round was needed. Reviewers have been selected partly internal and partly external to the book project. The editors are very indebted to the reviewers for their excellent and thorough contribution to the overall quality of the book.

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