Effectiveness of Disinfecting Wastewater Treatment Plant Discharges: Case of Chemical Disinfection Using Performic Acid

SIAAP
Service public de l'assainissement francilien

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Preface

Writing a book is not an easy task, as anyone who has ever written one knows. Besides the content, there are many questions to ask before successfully telling the story … A book to say what? For whom? In what form? And once you have all the answers to these questions, there is one last question that remains elusive: How do you tell the story? Raymond Queneau illustrates this difficulty very well by telling us in 99 different ways the simple story of a man traveling in a bus (Exercices de style, Raymond Queneau. 1947).

Regarding the subject of access to water, its use, and more particularly, on the subject of bathing in urban areas, the choice and the way of telling the story are even more complicated. There are not 99 but thousands of ways to approach the subject, thousands of ways to tell this story of primary interest to each of us. Each of these ways will be fair, each of these ways will answer many questions and fuel reflections … But each of these ways will also leave out a number of questions. To choose means to exclude.

As a public authority in charge of wastewater treatment, our role has been to tell the story of disinfection from a technical perspective. A technology has been chosen and tested, from laboratory scale to full-scale trials… From an idea to its industrial feasibility. We tried to answer all the questions that came to a stakeholder's mind, with an operator and an end-user eye. No bias on the results. No position taken on the technology. The objective of our story has been to give, in a factual way,

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the results of the tests, starting from the development of the protocols, passing through the evaluation of technology's effectiveness and the verification of its harmlessness on the environment. Thus, the reader can, at will, read all or a part of the book according to his own questions, expectations, and objectives … To tell his own story!

In order to be able to address all of these subjects, to answer all of these questions, we have put all the required skills around the table, ending up all together with 23 co-authors. This method of doing things is limitlessly rich since collective competence is much greater than the sum of individual skills and that's why all co-authors are named at the beginning of the book regardless to their specific contribution to each chapter. Only the fourth part includes the name of the contributors at the beginning of each chapter since these works have been added to the book to complete the overview.

We hope that you will have as much pleasure in reading this book as we have had in writing it…

Happy reading!

Vincent Rocher and Sam Azimi

Contributors

The editors

Vincent Rocher heads up Innovation at the Greater Paris Sanitation Authority (SIAAP). After completing his environmental studies with a thesis on the fate of micropollutants in the sewer system, he entered SIAAP to work as a member of the technical and scientific support team. As Director of Innovation, Vincent now works on defining and implementing SIAAP research and innovation policy, in overseeing: asset management aspects, operational control and optimization of the entire sanitation system, and preparation of technical specifications and future regulatory requirements. Leader of the scientific research program, he provides support to the Executive Board and all SIAAP operational departments on technical and scientific matters.

Sam Azimi jointly heads up Innovation at the Greater Paris Sanitation Authority (SIAAP). Following his studies with a thesis on pollutant transfer through the atmosphere in urbanized areas, Sam worked as Operations Manager at a wastewater treatment plant within the SIAAP jurisdiction. He commissioned and operated the plant for eight years before joining the Innovation Division. His main objective is to preserve the link between Research and Development activities in the field of wastewater treatment and the needs of plant operators to optimize their processes. His primary tasks are twofold: coordinate SIAAP's scientific research program, and provide expertise on the water treatment processes and environmental impact of SIAAP's activities.

Sam Azimi and Vincent Rocher

The editors would like to thank the co-authors, the editorial supervisor and other contributors of this book, details of whom are given below.

The co-authors

GREATER PARIS SANITATION AUTHORITY (SIAAP)

Romain Mailler is an environmental engineering scientist and head of an R&D Service at SIAAP's Innovation Division. He was awarded a PhD in Environmental Science and Technology in 2015. His work has focused on gaining an understanding of all types of sewage mechanisms. In particular, Romain is presently working on the coagulation/flocculation of wastewater, oxidation and adsorption techniques, the fate of micropollutants in sewage facilities, sludge rheology and thickening/dewatering, and membrane/concrete/metal aging in wastewater. He is also a co-leader of the research mission dedicated to material aging in wastewater facilities as part of the MOCOPEE program.

Sabrina Guérin-Rechdaoui is an environmental engineering scientist and head of an R&D Service at SIAAP's Innovation Division. Holder of a Master's degree in environmental engineering, she oversees development and deployment of innovative measures (physicochemical and biological) on environmental matrices. Sabrina is also in charge of the quality observatory for the Seine River in the Paris Metropolitan Area. She joined SIAAP in 2009 and began her career in process engineering. Extremely involved in research activities, she co-leads the MOCOPEE program's research mission on metrology and signal processing, in addition to being a member of the MeSeine Innovation program coordination committee.

Perrine Mèche is a research technician in charge of the technical platform dedicated to reagents used in wastewater at SIAAP's Innovation Division. Over the last

10 years she has conducted various studies on innovative treatment processes and reagent efficiency and characterization, spanning the laboratory, pilot and industrial scales. Perrine is currently working on mechanisms to better understand and optimize the various processes requiring the addition of reagents: coagulation/flocculation, biological treatments, and tertiary treatments by oxidation or adsorption, including wastewater disinfection.

Sébastien Pichon is a research technician in charge of the technical platform dedicated to process engineering studies at SIAAP's Innovation Division. He earned a D.U.T. professional degree in Biological Engineering (Lille University of Sciences and Technologies) in 1999 and prior to his current experience, Sébastien has conducted various studies in the field of wastewater treatment spanning the laboratory, pilot and industrial scales. He had also worked on developing a microbiology laboratory specialized in wastewater treatment and moreover conducted environmental and health studies related to the microbiological quality of water in cooling circuits.

Angélique Goffin is an environmental scientist at SIAAP's Innovation Division. She earned her PhD in Environmental Science and Technology in 2017. Before her SIAAP experience, she worked at the University of Paris Est-Créteil, in the Laboratoire Eau, Environnement et Systèmes Urbains (LEESU). Her focus lies in dissolved organic matter behavior in various aqueous environments. Angélique is also actively involved in developing multidimensional fluorescence spectroscopy with applications in surface water monitoring, water treatment and wastewater treatment. She received an award in 2018 for accomplishments in fluorescence spectra decomposition during the first international contest devoted to 3D fluorescence spectra in a parallel factor analysis.

Jean Bernier is an R&D engineer and head of an R&D Service at SIAAP's Innovation Division. He holds a PhD in Water Engineering, obtained in 2013 from Laval University, Québec. His work has primarily focused on modeling wastewater treatment processes/plants and river quality, as well as using these models in practical applications for SIAAP. In particular, Jean has worked on biofiltration, physicochemical primary settling, anaerobic digestion and membrane bioreactors. His work also entails automated data processing and sensor measurement validation. In addition, he is co-leader of the MOCOPEE program's research mission on modelling and process control in the area of wastewater.

Jérôme Roy is the Director of three SIAAP wastewater treatment plants. A graduate of ESTP Paris combined with a Master's degree in Environmental Engineering and Management from the ENSMP School, he began his career in the construction industry and quickly transitioned into the environmental protection sector.

He then spent nearly 15 years supervising the building of wastewater treatment plants for SIAAP. Since 2016, Jérôme has held the post of Deputy Director and then Director for the three SIAAP wastewater treatment plants located in the eastern part of the Greater Paris area, upstream along the Seine River. This unique geographic configuration makes these WWTP plants critical to hosting open water events at the Paris 2024 Olympic Games.

PARIS-EST CRETEIL UNIVERSITY

Gilles Varrault is a Professor of chemistry at the Laboratoire Eau, Environnement et Systèmes Urbains (LEESU) at the University of Paris Est Créteil. He obtained his PhD in the field of environmental sciences from the University of Paris VII in 2001. He was appointed to the post of Assistant Professor at the University in 2002 and received tenure in 2013. Until 2014, his research activities had mainly pertained to metal and organic pollutants in aquatic systems, with special attention focused on their bioavailability. Since 2014, Gilles has also worked on characterizing organic matter in receiving environments as well as in wastewater treatment plants through the use of spectrometric techniques. Furthermore, he helps develop sensors for the high-frequency, *in situ* monitoring of organic matter.

Julien Le Roux has been an Assistant Professor at the Laboratoire Eau, Environnement et Systèmes Urbains (LEESU) at the University of Paris Est-Créteil since 2015. He earned an engineering degree and PhD in Water Chemistry and Microbiology from the University of Poitiers (France) in 2008 and 2011. Before joining LEESU, Julien worked as a post-doctoral fellow at KAUST University (Saudi Arabia). He possesses expertise in water quality and treatment (especially oxidation processes), analytical chemistry (gas and liquid chromatography coupled to mass spectrometry, high-resolution mass spectrometry) for the analysis of organic micropollutants, identification of unknown compounds and elucidation of degradation mechanisms.

Nina Huynh holds an engineering degree from the Ecole Nationale Supérieure de Chimie in Rennes (France) and a Master's degree in water quality and treatment from the University of Poitiers (France). During her current PhD curriculum at the University of Paris Est-Créteil, Nina is involved in characterizing organic micropollutants in urban waters by means of high-resolution mass spectrometry.

Maolida Nihemaiti is currently a research scientist at the Helmholtz Centre for Environmental Research (UFZ) in Leipzig, Germany. She received a PhD from Curtin University in Perth, Australia in 2018. Before joining UFZ, she worked for one year at the University of Paris Est-Créteil with the Campus France Prestige Postdoctoral Research Program. Maolida's research interests include the fate of trace organic contaminants in various natural and engineered aquatic

environments and an analysis of their transformation products through the use of high-resolution mass spectrometry.

PAU AND PAYS DE L'ADOUR UNIVERSITY

Thierry Pigot is a tenured professor at the University of Pau and Pays de l'Adour and conducts research at the Institute of Analytical Sciences and Physio-chemistry for the Environment and Materials (IPREM UMR CNRS 5254). He heads the Federation of Research on Environments and Aquatic Resources, which brings together several research teams working in the field of water and aquatic environments. Thierry's particular research topics concern the study of chemical and photochemical oxidation processes and mechanisms applied to water and air treatment. He is also involved in several Bachelor's and Master's degree courses in the following fields: environmental chemistry, water treatment, organic chemistry.

Thomas Paulin is a research engineer at the Institute of Analytical Sciences and Physio-chemistry for the Environment and Materials (IPREM UMR CNRS 5254), currently responsible for IPREM's Chemical and Microbiological Water Analysis Laboratory in Anglet. Thomas was the operations manager during the study conducted on the performic acid disinfection process at the Biarritz wastewater treatment plant, where he coordinated all monitoring campaigns and environmental studies.

SORBONNE UNIVERSITY

Jean-Marie Mouchel is a Professor at the Milieux Environnementaux, Transferts et Interactions dans les hydrosystèmes et les Sols (METIS) unit at the Sorbonne University (Paris). As a trained hydrologist and biogeochemist, he led for 10 years the PIREN-Seine program, a vast project focusing on the functioning of the Seine River basin, viewed as a socio-eco-system. Jean-Marie presently heads the UMR 7619 Metis joint research laboratory (Sorbonne University, CNRS, EPHE) in the field of environmental sciences, whose teams are specialized in hydrology, near-surface geophysics, nutrient and carbon fate and cycling, and contamination studies. His primary research topics are dedicated to water quality, particularly in densely populated areas.

WATCHFROG LABORATORY

David Du Pasquier is a senior scientist at the Watchfrog Laboratory. He holds a PhD in Molecular Endocrinology and is specialized in endocrine disruption. He joined the company in 2006 to work on the development and use of *in vivo*

tests using frog and fish embryos for the detection of endocrine disruption in water samples, cosmetics or chemicals. David is a member of the OECD validation management group for ecotoxicity testing and sits on the OECD Chemical Committee. In these expert groups, he participates in the development and international validation of tests used for the regulatory assessment of chemicals with respect to endocrine disruption.

TAME-WATER

Laurent Paulic is a microbiologist with 15 years of experience at Tame-Water. He developed the company's technical product offering and oversaw its implementation with customers. From his initial training in the food industry, he worked in the pharmaceutical industry before focusing on plasma physics for 10 years in the field of controlling atmospheric contamination. A business developer who went on to become Laboratory Supervisor and President, Laurent's company was subsequently acquired by the Alcen Group. Since that time, he has been expanding the product side of the business, including the development and deployment of automated biosensors.

FLUIDION S.A.

Dan Angelescu is the CEO and R&D Director of Fluidion, founded in 2012. The company's activities are focused on novel technology approaches to the *in situ* chemical and microbiological analysis of water, wastewater and the environment. After completing his BS from the California Institute of Technology and his PhD from Princeton University (both in Physics), he worked as a senior researcher at Schlumberger Technologies, where he helped develop the first downhole microfluidic analytics platform. He then continued his career in academia, in being awarded the French Research Accreditation. As a Professor at the University of Paris-Est, Dan led a research group focused on the interplay between nanotechnology and microfluidics, with specific emphasis on novel sensors. In parallel, he taught classes in science and engineering disciplines, including a co-leadership position in an international Master's program. He has authored the book 'Highly Integrated Microfluidics Design' along with numerous peer-reviewed articles and patents in the areas of condensed matter physics, nanotechnology and microfluidics.

Vaizanne Huynh is an Operations Engineer at Fluidion. Following her Master's degree in Organic Chemistry, she undertook a Master's in Innovation at the Sorbonne University in Paris, where she joined the company FLUIDION for her Master's thesis in 2014. She initiated development of the pH sensor prototype and then, as an R&D Engineer, participated in the company's microbiology

sensor project. Vaizanne oversaw the metrological part of the FLUIDION microbiological sensor, known as the ALERT System. Since its release on the market, she has stepped into the role of Operations Engineer handling implementation, client follow-up and other projects. She has also co-authored several peer-reviewed articles in the fields of organic chemistry and microbiology.

Andreas Hausot is the team's Director of engineering at Fluidion. He holds a B.A. Sc. degree in Civil Engineering from the University of British Columbia (Vancouver, Canada) and is author of multiple patents and patent applications on technologies spanning oilfields, microfluidics, subsea monitoring and sampling. He has previously worked as Project Manager for downhole fluid analysis at several international locations with Schlumberger, leading engineering teams in developing sensors for extreme environments, with an emphasis on optical fluid analysis technology. Andreas is a co-founder of Fluidion and moved to France to become the team's Director of Engineering, focusing on the development of innovative new technologies for autonomous water quality measurements.

VERITAS S.p.A.

Patrizia Ragazzo heads the R&D–EU projects unit for the Integrated Water Service (IWS) of VERITAS S.p.A, the multi-utility managing Venice and Venice region's coastal areas, which encompass some one million residents. Before working with VERITAS, she was a researcher in the Chemical Engineering Department of Padua University and ran the R&D-Process Control Department of A.S.I. S.p.A, an IWS utility operating in northeastern Italy. Patrizia's field of research spans both drinking water and wastewater processes, having published some 80 papers in national/international journals and proceedings. Disinfection is one of her primary specializations.

Nicoletta Chiucchini is a chemical engineer at the R&D–EU projects unit of VERITAS S.p.A Integrated Water Service. Prior to this experience, she held the post of Assistant Manager for the R&D-Process Control Department of A.S.I. S. p.A, an IWS utility operating in northeastern Italy. Her work has mainly focused on wastewater treatment and technologies (management, optimization, upgrade, etc.) and related research activities to enhance processes. Effluent disinfection is among her areas of specialization.

The editorial supervising

Géraldine Izambart, head of the innovation management unit at SIAAP's Innovation Division and **Pauline Souchal**, from her team carried out the whole editorial supervising of the present book.

The contributors

In addition to the co-authors there are a number of contributors to this book who have provided significant assistance, in particular for the full scale trials detailed in part 2.

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General introduction

Over the past 50 years, the layout of the Parisian sanitation system has radically changed, shaped through three major milestones. Beginning in the early 1970s and over a 10-year period, a major industrial revolution led to a strong treatment capacity expansion at the Seine-Aval wastewater treatment plant, which would become one of the largest plants worldwide. This first step was followed by an another crucial 10-year phase, from 1980 to 1990, which focused not only on building new plants to bring on-line a significant increase in treatment capacity but also, and based on an intensive applied research activity, on preparing for the treatment plant changes required in response to environmental expectations. Lastly, the changes occurring during the past 25-plus years, from 1990 to present day, have been aimed at improving water treatment quality from removing only carbon to the complete removal of carbon, nitrogen and phosphorus (Rocher & Azimi, 2017). Such industrial changes have significantly contributed to decreasing pollutant discharges into the Seine River while restoring its physiochemical quality. Consequently, the oxygen level in the river is now quite good, and the nitrogen and phosphorus concentrations are much lower than in past years. These conditions favor the resurgence of numerous fish species, with a recent record of 32 (whereas only three were counted in 1970) (Rocher & Azimi, 2016).

The Parisian sanitation system now faces new challenges in managing the wastewater produced by nine million inhabitants in a densely urbanized area. More efficient use and management of wastewater are critical to addressing the growing demand for water and the threats to water security. In this context, the

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evolution of social expectations in favor of wastewater reuse and the City of Paris' pledge to open the Seine River to Olympic and Paralympic swimmers, as well as to all Parisians, in 2024 have brought the issue of bacterial pollution to the forefront (Directive 2006/7/CE, 2006). This issue seeks to identify and quantify the main input pathways of bacteria into the river (treatment plants, storm overflows, etc.) in order to define the best action plan for achieving the recreational use objectives. Various solutions have been devised on the scale of the Paris Metropolitan Area, and scenarios have been tested using the PROSE mathematical model to establish and prioritize the actions to be carried out. PROSE is a modeling tool, calibrated and validated on the Seine River, intended to simulate nutrients and bacterial contamination within the Parisian watershed; moreover, since 2007, it has been used by the Greater Paris Sanitation Authority (SIAAP) to design the Greater Paris sanitation master plan.

For all scenarios examined, disinfection of the effluent conveyed by the wastewater treatment plants located upstream of the City of Paris appears to be a necessary action. Indeed, bacterial contamination of the Seine River has been shown to be significantly higher downstream of the wastewater treatment plant outfalls (Figure 1).

During dry weather conditions, wastewater treatment plants significantly contribute to bacterial concentrations in the river. The median concentration discharged into the river has ranged from 5×10^3 to 50×10^3 MPN/100 mL of *Escherichia coli* (*E. coli*) (Rocher & Azimi, 2016), leading to a median concentration level in the river of 1200 MPN/100 mL at the Port à l'Anglais site, located downstream of the outfall. Thus, to be compliant with the bathing quality objectives, the disinfection of the outfall becomes crucial to limit the bacterial concentrations in the river. The situation is quite different during rain events. Relying mostly on a combined sewer system, the Greater Paris Sanitation Authority operates more than 400 km of pipes to handle wastewater for treatment into six plants. While during dry weather periods the facilities are able to treat the entire flow, such is not always the case during wet weather periods. During rain events, due to the high level of impermeable surfaces, additional rainwater significantly increases the flow rate into sewer pipes and exceeds the drainage and treatment capacities of the whole sewer system, thus inducing combined sewer overflows (CSOs) into the river. This untreated CSO discharges water, containing up to 5.5×10^6 MPN/100 mL of *E. coli*, into the river (Rocher & Azimi, 2016). In this case, CSOs become the main introduction pathway of *E. coli* into the Seine River (Figure 1, yellow curve, occurring during the rain event after 28 hours of simulation) and the disinfection of the plant outfall, which was of prime importance during dry periods, appears useless for the river to be compliant with bathing quality objectives

While the main objectives for the years ahead concern the ability to manage rainwater in compliance with the water framework directive (WFD, 2006), tackling the bacterial contamination due to wastewater during dry periods

becomes of critical importance in significantly reducing the Seine River contamination level. Though Rocher and Azimi (2016) have shown that conventional wastewater treatment facilities offer a satisfactory bacteria removal rate (ranging from 2.76 to 3.03 log for *E. coli* and 2.73 to 3.37 log for intestinal enterococcus), it would appear that additional treatment processes are still required in order to significantly reduce the bacterial contamination of WWTP outfalls.

To help stakeholders in their choice for any additional treatment, the SIAAP has integrated into its scientific program, through its Mocopée research program, an action to study the disinfection processes and their effectiveness and harmlessness to the environment.

Among the technologies currently available for disinfecting wastewater outfalls, chemical disinfection appears to be a well-adapted solution due to both its operational flexibility and efficacy at removing bacterial contamination. While several chemicals are known to disinfect water, performic acid (PFA) is currently being used by some municipalities (Biarritz, France and Venice, Italy). This is the basis for SIAAP's testing of PFA to disinfect its Seine Valenton wastewater treatment plant outfall. A two-year study was performed both in the laboratory and at full-scale. This provided answers regarding both the efficacy and the absence of environmental impact of this disinfection process. This book sets out and discusses the expected outcomes of using PFA under three headings:

- Assessment of the efficacy of this type of chemical disinfection on WWTP outfall;
- Technical feasibility of full-scale implementation;
- Verification of the minimal impact on the River Seine.

A fourth section, which reports feedback from the municipalities where PFA disinfection has already been implemented, serves to complete this overview.