Hydraulic modelling of liquid-solid fluidisation in drinking water treatment processes

Onno Kramer


Water
Data
Drinking
Particle
Models
Fluidised
Treatment
Pilot
Hydraulic
Sustainability
Softening
Plant
Flows
Innovation
Multiphase
Sensor
Prediction
Number
Drag
Cfd
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Etsw
Education
Process
Quality
Soft
Solid
Symbolic
Delft
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Heterogeneous
Carbon
Froude
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Valorisation
Reynolds
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Settling
Calcium
Machine
Kozeny
Control
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Computation
Based
Terminal
Green
Dynamic
Reactor Cycle
Accurate
Enhancing
Velocity
Regression
Grains
Economy
Materials
Liquid
Driven
Relations
Optimisation
Homogeneous
Richardson
Hydrostatic
Dashboard
Zaki
Pellet
Automation
Raw
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Factors
Synergy
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Technology
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Acknowledgements

“A civil servant should be able to make music all day, following the Cuban model.”
(Onno Kramer, 2021)

1 Acknowledgements

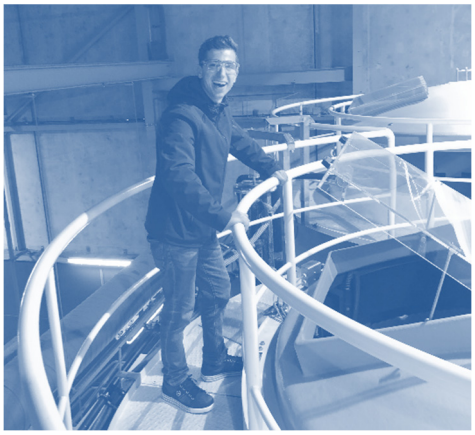
1.1 Once upon a time

First and foremost, I would like to express my gratitude to Eric Baars. In 1989, I was looking for an internship to gain experience in the field of water treatment. After the summer, Eric gave me a chance to start working for Gemeentewaterleidingen Amsterdam. On the first day at work, Eric showed me around the Weesperkarspel pilot plant where he was working as a research fellow. He quickly shared the most important insights concerning the backwashing principles of the rapid sand filters, and he also taught me how to titrate the softening effluent. That said, Eric was in a bit of a hurry: he had planned a number of holiday activities. He had to dash, so he left me alone in the pilot plant. I had to figure out myself if the backwashing procedure should be executed with water, with air, or with both. This occasion proved to be a crucial experience for me, since it really forced me to start 'thinking' and subsequently make a sound decision. Fortunately, this worked well, and a disaster (flushing sand out of the column) was prevented. Eric's *secret* was that he treated me with me respect and gave me a sense of responsibility and trust. Even now, these attributes are a wonderful inspiration for me in my role as supervisor.

By working hard, I acquired the luxury of having some spare time. During these spare moments, I set up a tiny vertical cylindrical column, fed it with tap water and fluidised granules. I filled the column with garnet sand and measured the expanded bed height for various flows. The Head of the Research and Development Department, Dr. Graveland, provided me with a number of articles and books about fluidisation. I found several prediction models, but none of these yielded predictions that would even come close to the measured bed height. In 1991, Eric allowed me to try and unravel this mystery of the expansion conundrum during a BSc graduation project. Barely two weeks before the thesis submission deadline, I found a possible answer to this mystery. The solution included a prediction model for the expansion behaviour

of irregularly shaped garnet and calcite pellets in water. For many more years, I was able to continue working with Eric on this subject during summer projects. Eventually, in 2016, I started a PhD project to study the flow of particles in water. Eric, I am forever grateful to you for seeing the holy fire burn inside me, for inspiring me, and for marvelling with me about how the mysteries of the dancing-grains-in-water work. Eric has many adages: “You learn the most in front of a class” and “You only get it when you see it”. How very right he is.

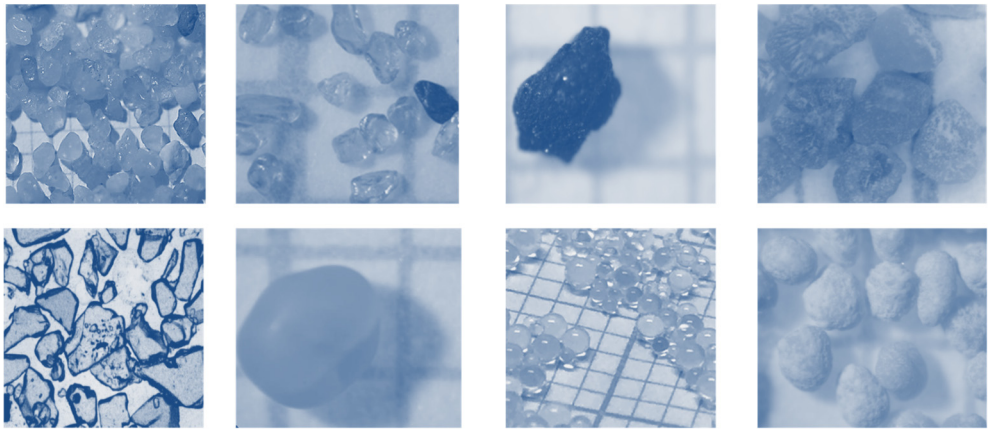
1.2 There may be a hundred counter arguments, but only one argument is needed to make the move



In 2016, Eric Baars, Peter de Moel (TU Delft) and myself were assisting graduate student Liselotte van der Hout during her final project on chemical performance in pellet softening reactors. To be able to predict this performance, a voidage prediction model was needed in a so-called layers model. Prior to this, in 2014, I had written my first conference paper about well-known voidage prediction models and presented my work at the IWC International Water Conferences. Peter said that he did not ‘believe‘ my model, so that is what sparked the competition between him and me. The goal was to find the best prediction model. I must confess that Peter won, but Liselotte had a much better plan in mind. Liselotte said: “Onno, why don’t you start a PhD project about this topic?”. By coincidence, I had a progress interview with my manager Leon Kors that afternoon, which presented me with a wonderful opportunity to share my PhD idea with him. Leon answered: “Yes, when will

you start?". That same week I wrote my preliminary PhD proposal and presented it to my Waternet colleague Jan Peter van der Hoek (also a professor in Delft). A dazzling two weeks later I found myself enrolled at the Delft University of Technology. Thank you, Leon and Jan Peter, for your trust and willingness to support me with my PhD plans. Liselotte, thank you for reminding me that I had gained more than enough substantial knowledge about granules in water by carrying out so many student projects. Jan Peter: I learned so much from you about scientific writing. I greatly appreciate your uncluttered, detailed, structured, focused and highly scientific approach. Leon: you are the best manager I have ever had.

The battle between Peter and me lasted throughout the PhD period. Seldom have I met someone like you, Peter, so unrivalled and so resolutely knowledgeable about a myriad of topics, such as engineering, hydraulics, aquatic chemistry, modelling, data processing and visualisation, scripting and many, many more. Working with you was more than a pleasure, even though you roasted my work more than once. Despite your keen eye and frequent roasts, however, it seems you've finally lost this battle. Still, and here I am using Eric's words, *the apprentice surpassing his master* will inevitably happen to me too.

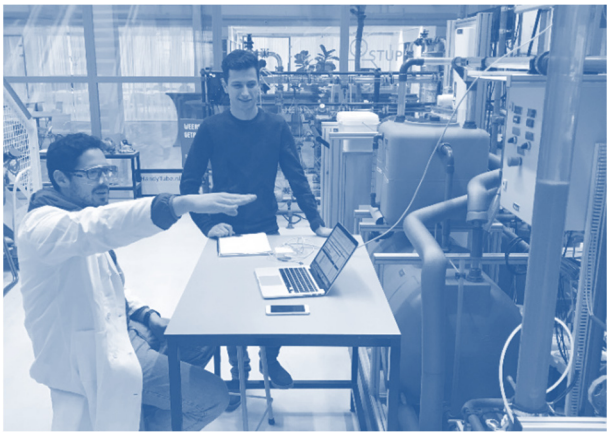


I asked myself more than once why I started this PhD project in 2016. After all, there was no pressing need to embark on this journey: I would simply continue to work for a respectable water organisation in a wonderful team. I would also remain a supervisor of many students, blessed with the opportunity to devote myself to research, and I expect that very little will change after I have defended my thesis. In other words, engaging in a highly exerting and time-consuming PhD programme

would seem to have more cons than pros. Still, imagine that I had listened to all kinds of voices expressing all kinds of counter arguments, then I would never have met all these beautiful people. I am glad that I decided to move ahead with my PhD journey.

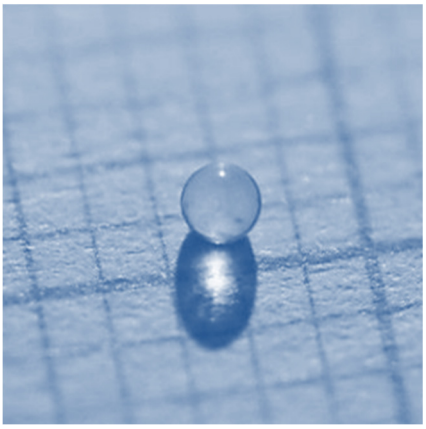
1.3 Life is about juggling obligations

The first week after kick-starting my PhD work, I learned that a *Doctoral Education Programme* is a mandatory part of any PhD project. In total, 45 Graduate School credits have to be earned. No, this did not put me off, despite the grumbling noises I heard about this requirement from numerous other PhD students. I decided to apply the *front-end loading* strategy, also referred to as *pre-project planning*, which I had learned from my oldest brother Sven. And I learned from my other brother Jurgen to ignore all *glass-half-empty* opinions. In merely two years' time, I gained more than 50 credits. More importantly, I learned a lot, so I could put this knowledge to excellent use for the benefit of my PhD project. Thank you, Ilse Donk and Giovanni Bertotti of the TU Delft Graduate School for your seminal advice.



In addition, I also want to express my gratitude to Hemmo Abels for being my PhD mentor. Juggling obligations was a positive experience in the end, despite the huge investment that this took. I also appreciate the TU Delft secretariat for all the support in recent years: Mariska van der Zee, Sabrina Kestens and Leslie van Leeuwen.

1.4 Beautiful paths are revealed by getting lost



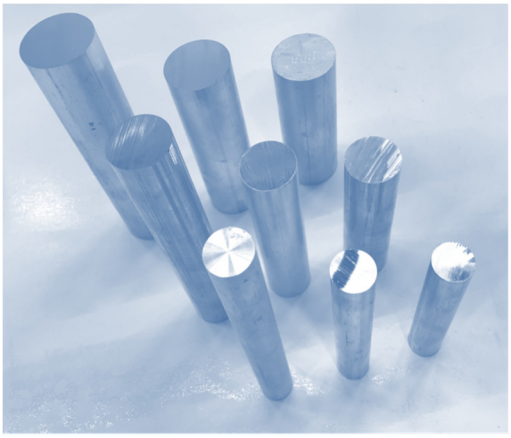
During my PhD project, I worked with dozens of inspiring students. It was an honour to be their supervisor. Awad Elarbab and Sam Rutten, my first students of chemical engineering during my PhD project, graduated simultaneously in 2017. They both worked with the expansion columns in the pilot plant at Waternet. Awad, I cherish the moments that we tried to solve the relation between the interstitial and terminal settling velocity on a flip chart. Awad: أنت شخص مميز جدا. بالتوفيق جزاكم الله خيرا صديقي عوض. Sam, you revealed the Extended Terminal Sub-Fluidisation Wash with your 'hydraulic garden-hose' hypotheses. You are a wonderful bloke. Sam: good luck with your PhD. In 2016, Sven Schoonhoven and Jasper Steenbrink worked on the improvement of the *Waterkwaliteitsverstoringsmodel*. This model remains a useful tool for Waternet. Of all students, Anthony van As proved to be a master at working precisely and accurately. Not once did I notice him slacking during the execution of experiments. Anthony: wanneer gaan we weer op pad om Brabantse Worstenbroodjes te scoren? In 2018, Eleftheria Chiou worked very hard on the modelling of pellet softening reactors. She discovered the 'hockey-stick' curve in the complex softening chemistry. Eleftheria: Ευχαριστώ για τις υπέροχες στιγμές στη βιβλιοθήκη με καφέ και μπισκότα. Θα

δούμε ο ένας τον άλλον στην Ελλάδα το επόμενο έτος. In 2018, Jos Vantomme studied the expansion behaviour of almost perfectly spherical glass beads. Jos, you can be very proud of yourself: you joined me in Eindhoven where we presented our work at a PhD lecture for the prestigious TU/e Multi-scale Modelling of Multi-phase Flows Group. I also owe a big thank you to

Kay Buist and Hans Kuipers for sharing their expensive and valuable spherical granules for the benefit of our experiments. Jos' partner in crime was Rens Kuijpers, who compared different techniques to crush or grind calcite pellets. Rens: heb je het boek van Stephen Covey nou al gelezen? Johan: I hope you are doing fine. Lars van Bokhorst, a qualified chemistry teacher, started his research assignment to obtain his Master of Education certificate. He studied the opportunity to crack calcite pellets using cavitation. Lars: wat een inspiratie was het om met jouw enthousiasme naar scheikundige uitdagingen te kijken.

Pablo Daniel Dacomba Torres started his graduation project at Waternet in 2018. He had the courage to look for a prediction model for the most complex granules you can ever imagine: polydisperse, tremendously irregularly shaped and also porous granular activated carbon grains. But you did it man. Compadre: has trabajado muy duro y has logrado mucho. No olvide pescar. Entonces, ¿es Daniel o Pablo?. Rubayat Sobhan continued Eleftheria's work on the softening chemistry in 2019. When we set out on this path, we did not realise that the inhibition chemistry was even more complex than we initially expected. Ruby: সাফল্য অর্জনের পরে চিরতরে টেবিলে নাচতে থাকুন. During my stay in London in 2019, Cas van Schaik applied for

a graduation project. That his supervisor was not there to hassle him had a positive side effect. Cas designed a completely new differential pressure measuring panel for the complete reactor height and installed it at HU Applied University. Cas: ik ben een gelukkig mens dat ik je mocht inhuren in de laatste fase van mijn PhD. Je bent geweldig. Laten we snel naar London gaan. Like Lars, Suraj Ramjad started his Master's project investigating the influence of irregularly shaped particles on the effective specific surface area. Suraj: सूरज पर लटकाओ, तुम लगभग वहाँ हो. There are students who work hard, but Victor Yoyo Shao works hard as well as unbelievably fast. In 2020, Victor examined the expansion behaviour of almost every granule type you can find in the lab. Victor: 朋友，別跑得太快，說不。你是一個很棒的人. I first met students Phoebe Berhanu and Jamila Rahman of Queen Mary University of London in 2019. They then applied for a full year of industrial placement at Waternet. Phoebe studied rapid (not rabbit) sand filtration and Jamila specialised in the image analysis of high-speed camera films of calcite pellets. Phoebe: ፌቤ ፡ የአየር ንብረት ለውጥ በጭራሽ ለእርስዎ ሞጥፎ ነው ብቤ አላስብም., Jamila: বিশ্বাস করাটা সুন্দর বলে মনে হয় এটি সর্বদা নয় এবং আপনি এটি স্বয়ংক্রিয়ভাবে ফিরে পাবেন. The last students during my PhD project were Roy Duijnmaijer who explored the application of the hydrometer in full-scale reactors and Aisha Malik who showed her passion for the water world. Roy: wat een indrukwekkend lange weg heb je afgelegd om tot ingenieur te komen. Proficiat. Aisha: صبر کرو۔ اپنے والد کو میری نیک تمنائیں۔.



1.5 Education is the gateway to the future

In addition to individual graduation projects, I also guided other student projects, for instance Minor's projects. In 2018, Sercan Akcay and Rens Kuijpers were the first to work with a brand-new expansion column set up at Applied University in Utrecht. Students Timo van Bergen, Herman Klok, Stan Turk and Michel Vrieswijk developed an ingenious method to analyse the particle size distribution of granules. They were awarded the HU '*Pearl*'-projects-with-impact prize and were invited to present their work at the opening of the academic year. In 2020, Martijn van Leusen, Patrick Brakeboer, Chelsea Sarkam, Roy Duijnmaijer and Jelle Baars worked together on the development of the immersed hydrometer in a fluidised bed.

1.6 Write with the door closed, rewrite with the door open

During my PhD project, I acted as co-supervisor and advisor for several other graduation projects and assignments. At University Utrecht, for Prof. Mariette Wolters: Sergěj Seepma in 2018, Tim Bögels in 2019 and Tom Bastiaan in 2020 who wrote excellent reports about softening chemistry. At HU: Herman Klok in 2018, Bas Verduijn, Pjotr Carelse and Jeroen Rademaker in 2019 wrote about process control

and energy recovery from water, and Arjan Haket, Geir Jacobs, Stefan Reijnders, Thijs Gouka and Yashvant Jhingoer wrote about olivine in water. All excellent work.

In the summer of 2019, we started a project at QMUL to examine the expansion behaviour of granular activated carbon grains. Thank you for your enthusiasm: Safia Norzai, Fouzia Ahmed, Faris Akhtar, Sofian Jasrai, Jamila Rahman, Nabila Rahman, Phoebe Berhanu, Arza Zenuni and Hassan Ibrahim. Joppe Kroon (TU/e) worked on CFD simulation to mimic liquid-solid fluidisation experiments conducted at QMUL. I am excited about your extremely important contribution aimed at enhancing the viability of this complex modelling. Tim Nijssen, working with you was a privilege.

1.7 Closing gaps through education

I would also like to thank the following *army* of students, colleagues, family, friends and others. Thank you very much for your contribution: Abdul Rauf Ahmed, Abduljapar Mohamed, Abu Hanif, Adrian van der Stok, Alessandro Di Bucchianico, Alexander Roling, Amir Shokir, Anne Offeringa, Arjan Haket, Arza Zenuni, Auke Smet, Bart de Ruiter, Bart van de Rotten, Bart Verkooijen, Bas Bouwman, Bas Verduijn, Belal Sharifi, Ben Cools, Brigitta Bunda Kuipers, Celina Carty, Cherany Grant, Clemy van der Steen, Colleen Quigley, Damylle Schoonhoven, Dap Hartman, David Ancieto, Dennis van den Pol, Desmond Lawler, Django Rossa, Edelmar Crichlow, Elyah van Fredrikslust, Ernst Jan Nijhof, Evelien Koenders, Eveline Glasbergen, Eveline Kramer, Faris Mohammed Akhtar, Feiko Riks, Floran de Bruin,

Fouzia Ahmed, Gaston Kross, Geir Jacobs, Gerard Visser, Gerrit Jan Zweere, Hanna van Benthem, Haseeb Mohammed Sheikh, Hassan Ibrahim, Hassan Saleh Abdulrahim, Henk-Jan van den Brink, Ibrahim Al Kathemi, Iloy van Genderen, Ishak Mohammed Hussain, Ismail Boutalab, Jack Schneiders, Jacob George Thomas, Jan Bruinsma, Jantinus Bruins, Jason Elliot Lauffer, Jelle Langedijk, Jelle van den Berg, Jelle van Hattum, Jeremy Scheffer, Jeroen Rademaker, Jimmy Sendar, Joas Wisse, Jochem Sluijter, Joep Kramer, Joep Lebouille, Jonathan Mafaabi, Jort Heijnen, Jos Hooft, Jules Engelen, Juliette van Gelder, Jurgen Molenaar, Justus van Rijnbach, kabita Kandel, Karin Bosklopper, Kawa Sarwar, Kevin Hoffer, Khalid Aalbasmana, Kim Van Schagen, Ko Rijpkema, Lars van Giessen, Laurens van der Vuurst, Leon

Ly, Lindsey Kartodikromo, Marc Teunis, Mariette van den Brink, Marijn Companjen, Mark Jobse, Martijn Vermeulen, Menno Schaefer, Mizanur Rahman, Mohamed El Mokaddam, Mohamed Shaabdi, Mohammad Ahmad Raza, Muhammad Ridwan Rashid, Nabila Rahman, Naim Ahmed, Niels Manders, Niels van den Hooven, Obaidullah Waheed, Okash Omar, Osman Osman, Pablo Borkes, Pjotr Carelse, Rachel Yu, Reem Abdulla, Rem co Vasterink, Renée Beckmann, Rick Arends, Rob de Wit, Robert Babuška, Rogier Elgin, Sadaf Shirazi, Safia Norzai, Saira Alam, Samin Nazarpouri, Sander Schellinger, Sanne Wolf, Sarah Schaper, Sem Schuring, Sercan Akcay, Sharmarke Abdi Mohamoud, Shazzad Hussain Miah, Siebe Spee, Simeon Joshua Ade Adesanya, Simon van de Kolk, Sofian Shahid Jasrai, Soufian

Chaiat, Soumaya Aissa, Souraya el Abdelkhalki, Stefan Reijnders, Stephan van de Wetering, Stephan van Eeten, Steven Visser, Susana He Wu, Susanne Grünewald, Syed Minhas Shah, Sylvia Jansen, Tariq Hennache, Thijs Gouka, Thomas Groot, Timo Ponsioen, Timo van Bergen, Tobias Nooij, Usman Lalustani, Vincent Siekman, Walter Goossens, Walter Menkveld, Warsame Rayaleh, Weronika Maria Lipien, Wessel van Haren, Willem Anker, Wim Oorthuizen, Wouter de Groot, Wouter Vos, Xavier Karl Letimier, Yara Said Abdelmoety Marzouk, Yashvant Jhingoer, Yousof Fazelpoor and Youssef El Bouhassani.

1.8 Anyone who has never made a mistake has never tried anything new

Since 2014, I have spent approximately one day per week in Utrecht at the HU Applied University of Utrecht to combine practice, research and education. This was a driving force for initiating a preferred partnership between Waternet and HU. We designed the expansion column for fluidisation experiments which soon became a part of the HU curriculum. Ellen Hilhorst, former director of the ILC: you made all of this possible, and working with you was a true pleasure. Many thanks to you and all the lecturers: Michiel van de Stelt, Jeroen van Gestel, Joep Hamerlinck, Jens van Riel, Joop Slaa, Arjan Brenkman, Richard Rigter, Hermen Bollemaat, Geert Schoenmaker, Patrick Cramers, Benjamin Broeze and many others. I enjoyed working with you all. Wim van Vugt deserves a special word of thanks from me. I hugely appreciated all the feedback you gave to me and to many students concerning statistics, physics, math issues and much more. I hope we will continue to do this in the future.

1.9 Not all those who wander are lost

Without the excellent technical skills of the pilot plant employees at Waternet and HU-ILC, my research would have been absolutely impossible. In the blink of an eye, failed components were replaced or repaired. There was always room for new ideas, despite completely overloaded calendars and schedules. Peter Wind, Mark Heuver and Fred te Pas, thank you for your invaluable assistance. Richard Rigter: I am grateful that you always helped us out in preparing even more experiments, setting up schedules, helping students, replacing grains and much, much more. Mark Joosten and Michel Colin, working together on the assembly of the QMUL

transportable expansion column in London was an awesome experience. When are we going back?

This brings me to London, where I stayed in 2019. Edo Boek: thank you so much for allowing me to hang around at the Queen Mary University of London, at the Division of Chemical Engineering, School of Engineering and Materials Science. I left for the UK to work on my English transferable skills: this was deemed a good idea since my own educational period was taught in Dutch. The moment I arrived, you immediately re quested me to teach 42 chemical engineering students at QMUL - in English. How is that for being thrown in at the deep end. Thank you, Benjamin Gridley, for giving me access to all the lab facilities. Julian Glover, it was a pleasure to have a British roommate. Edo: our numerous lunches with fish and chips are unforgettable. You told me that the transportable expansion column, my *dowry*, was a gift from heaven. According to most of the students, working with the expansion column was a greatly appreciated part of their study. Using the challenge-based learning method, we trained them to become skilled T-shaped, 21st century engineers. Together, we initialised the Minor programme in *Water Technology* where students had to design a cost-efficient, sustainable and reliable drinking water treatment plant. Edo, I hope

that I can hang around again at QMUL very soon. Finally, I want to thank Tim van Dijk (Brabant Water), Michiel van de Stelt (HU-ILC), Leon Kors (Waternet), Fenna Philipse (Waternet) and Raymond Pieters (UU) for working together in this completely new and innovative educational module on water technology. Thank you, Marcel Bakker, for facilitating the RHDHV *Cost Standard* so students were able to design and assess their water treatment plants.

1.10 Water is the driving force in nature

Besides all the PhD research work, I almost forgot that I also have a 1 FTE fulltime job at Waternet. My job is to improve the water cycle: an inspiring and challenging task, with plenty of inspiring work and challenges. I am grateful that my colleagues in the Water Quality team always showed their interest in my PhD work. A wonderful team to be a part of. Thank you, Yvonne Nijdam, Fenna Philipse, Joost de Munk, Robert van der Kleij, Rob Koeleman, Steven van Duijvenbode, Fred van Schooten, André Burger and Leon Kors. Jos Hooft, you are the best office roommate I have ever had.

I also really enjoyed the conversations I had with my Waternet colleagues, all of whom have so much field experience. Jan van Duijvenbode, Sean Willemse, Marcel Borsboom, Frans Twigt, Frank Smits, Geertjan van Heck, Pieter Nijdam, Alex van der Helm, Wil Selles, Peter Beemsterboer, Marco Dignum, Cheryl Bertelkamp, Epco

van der Meulen, Sophia Loch, Rob Groenen. Jan Hangelbroek, Ben Vermeulen, René van der Aa, Yolanda Dullemont, Petra Scholte, William de Goei and too many other pleasant co-workers to mention by name.

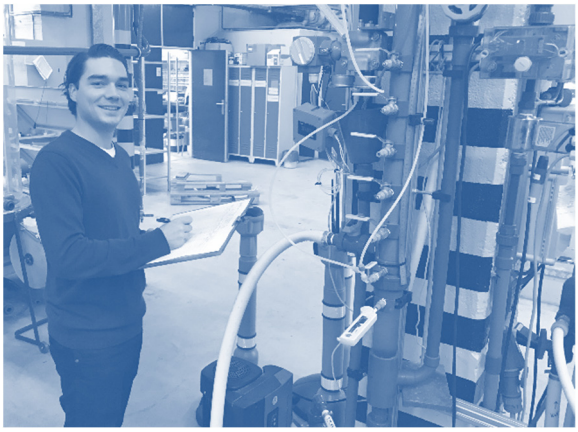
In addition, I want to thank other colleagues who were an inspiration for me to start this project. From Delft University of Technology, I owe thanks to Robert Babuška, Luuk Rietveld, Hans van Dijk, Wim Uijttewaal, Shravan Raaghav, Yousef Hasadi and Wim Paul Breugem. From RHDHV: Kim van Schagen, from ABB: Ben Smaal, from Aqua Minerals: Olaf van de Kolk, from Waternet: Karin Bosklopper, from Hoogheemraadschap van Rijnland: Alex Veersma, from PMconsult: Jan Timmer, from Evers & Manders Consult: Joost Jongerius, Johan Evers and in particular Paul Manders.

I enjoyed the discussions with Calima Tang and Cecilie Perch Hellinghus about whether or not to start pilot plant research. A final word of gratitude and thanks is due to Walter Goosens. Walter, you prove that age says nothing about being energetic and being inspired as well as inspirational. I sincerely hope that when I am

nearing my ninetieth birthday, I shall still have the ability and inspiration to produce the type of high-quality scientific work that you publish.

1.11 The mysteries of complex fluids are like butterflies

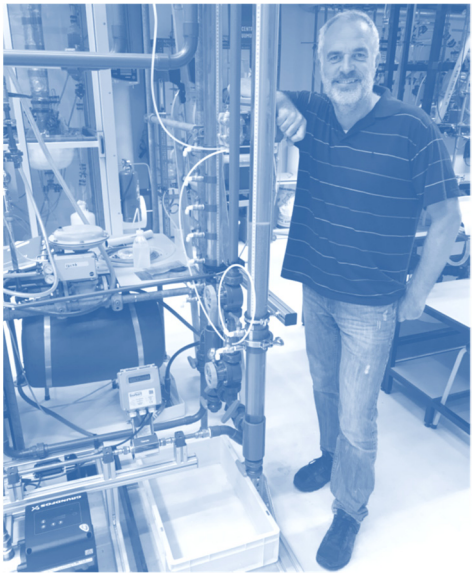
After my PhD-go/no meeting in 2017, it became clear that we needed an extra expert on multiphase flows. During a Graduate School course, PhD colleague Rumen Georgieva gave me the advice to have a chat with Prof. Johan Padding. It turned out that Johan was the perfect candidate for me. I wrote him a letter and soon after that, he became my daily supervisor. Once a month we had a meeting in the Process and Energy building. More than once we forgot to refill our coffee cups during our endless discussions to solve multiphase flow puzzles. In 2019, we attended the 10th International Conference on Multiphase Flow in Rio de Janeiro, Brazil, together. This was a wonderful opportunity to present my work and converse with experts from all over the world. During one session, Johan asked me to share my opinion about the contents of a presentation. I had to confess that I was completely lost and could not follow any of what the speaker had presented. Johan then suggested that we should return to the hotel to have a look at my model. I must confess, Johan, that this was by far the most enjoyable experience for me during the entire week in Rio. It was during these hours of



creative work in the hotel lobby that we invented the RIO model. This model became the foundation of my second paper, published in Elsevier's International Journal of Multiphase Flow. Johan: meeting you and working with you helped me deepen my knowledge and broaden my views on multiphase flow. Let's have more coffees and discuss new challenging topics.

1.12 Non nobis solum nati sumus

A few extra words of gratitude are reserved for a number of people. Special thanks go to Laetis Kuipers, who checked and edited my manuscripts and helped me improve my English speaking and writing skills. Laetis: let's meet and enjoy British crumpets. Special thanks are also due to Dr. Bouke Hora Adema for sharing several decades worth of insights with me and for offering perspective. Thank you Miloš Bunda, for having discussions about education, research, technology, entrepreneurship and next generation engineers. Finally, I want to thank my family and friends for supporting me, and in particular my parents in law for allowing me to struggle with all my math puzzles during our holidays. Your unconditional support and your interest in my work and wellbeing are awesome. I am a privileged person. I would like to conclude my acknowledgements by thanking my PhD team members: Jan Peter, Johan, Eric, Peter and Leon. You have provided me with so much knowledge, shared your experience in many fields, outlined inspiring visions, showed the big picture, gave valuable feedback, helped me gain a clear focus, and much more.



My final words of gratitude are for Karin: you are the very best that has ever happened to me!

Onno Kramer, Weesp, 2021.

Water is van iedereen

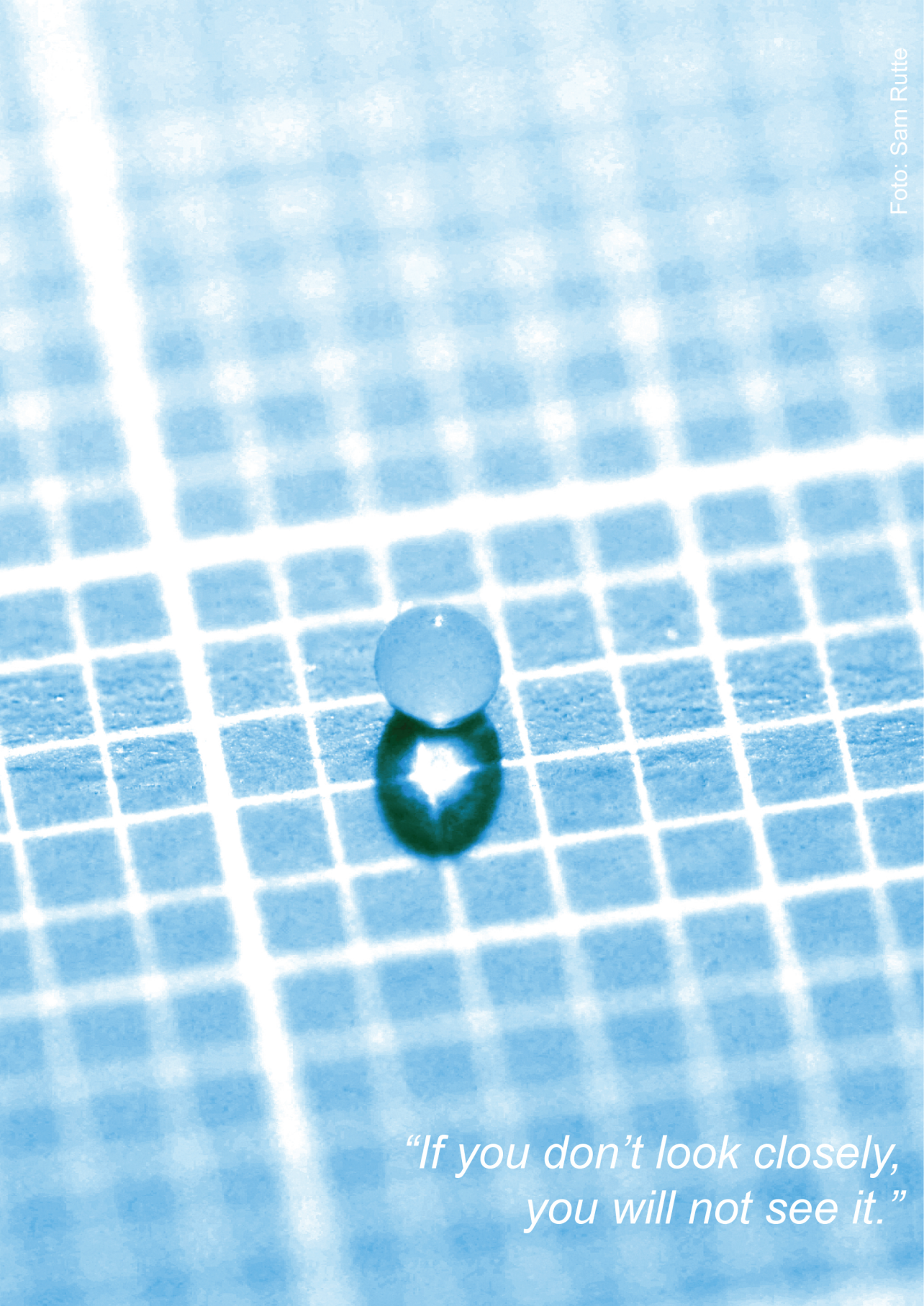


Foto: Sam Rutte

“If you don’t look closely,
you will not see it.”