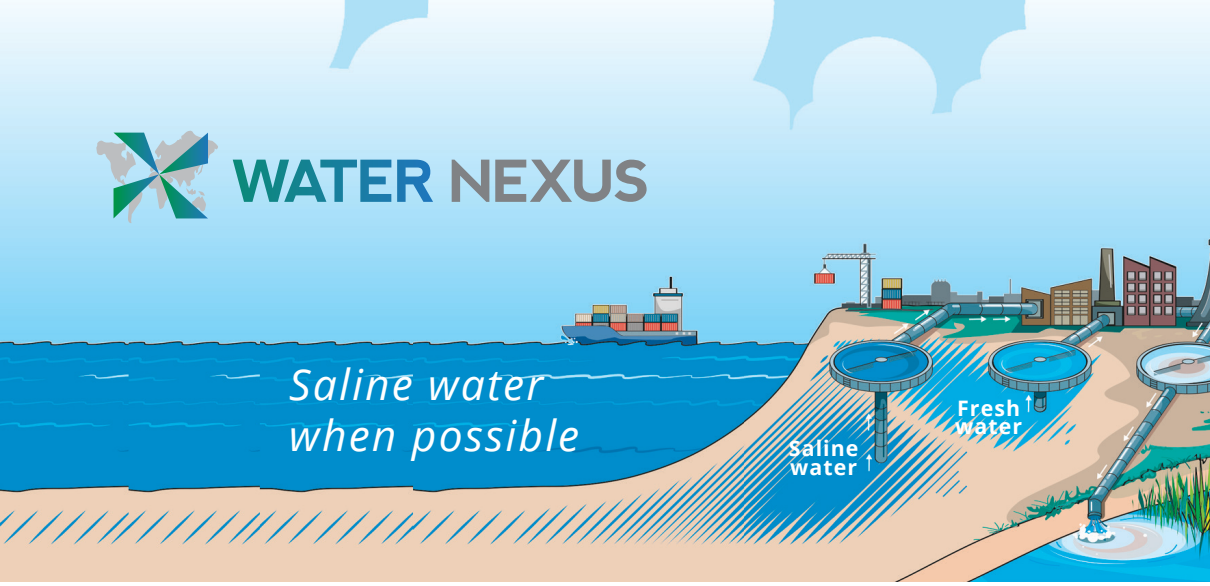
WATER NEXUS

Saline water when possible

Fresh water when needed

Final report


WATER
NEXUS



Preface

The Water Nexus program was an adventure starting already in 2012, with discussions among representatives of the Dutch industrial sector, including Dow Benelux and Shell, and a group of scientists, including myself. World-wide, these multinational companies reported to see two main water problems. One is the increasing difficulty in providing water for industries, and the increasing efforts needed to avoid competition with drinking water, agri-food and nature conservation sectors. The other problem is formed by barriers in reuse of industrial waste water effluents and produced waters, potential resources to help to resolve water scarcity problems within industries, in agriculture and ecosystems. Climate change and sea level rise worsen these two problems, making fresh water less available, and increasing the influence of salt waters on local and regional fresh water availability. This is especially a problem in delta and other coastal regions in the world.

From these discussions, the idea of a new research program on sustainable industrial water provision arose, named Water Nexus. The word Nexus refers to the connectivity between the natural and technical water system and involving all sectors. The slogan “Salt water when possible, Fresh water when needed “ was put forward, because salt impacts on water resources appeared to be an overarching problem. In a follow up, discussions were held with representatives of drinking water companies, such as Evides and Oasen, WLN, water authorities, and technology providing companies, such as RoyalHaskoning-DHV, Paques, Nijhuis Industrial Technologies, and Witteveen+Bos which together with other stakeholders reconfirmed these findings and offered support to initiate the Water Nexus research program. Especially the idea to find a generic approach to solve water provisions problems on a local to regional scale, by involving local relevant stakeholders was highly appreciated by the The Netherlands Ministry of Infrastructure and Water Management, promoting the self-steering and water regulating capacities of the various regions in the Netherlands.

With these ideas and support from practice in our hands, the Water Nexus program and consortium were built, inviting Prof Marc Bierkens of (UU) and Prof Sjoerd van der Zee (WUR) to lead the research on strategic and local management of groundwater and the role of fresh-salt water interfaces. Prof Marc van Loosdrecht (TUD) and Dr. Hardy Temmink (WUR) concentrated on effects of salt on granular sludge based biotechnologies used for purification of effluents with high loads of organics. Prof Kitty Nijmeijer (TU/e) lead a group of scientists on membrane and electrochemical technologies to purify salt impacted waters. As coordinator and working at WUR, I had the honor to lead a group to study the design of sustainable water provision at local scale, integrating the above research lines into one unified approach. Sites of Dow in the Netherlands and Shell in Oman were taken as example. We included nature based solutions, such as constructed wetlands, removing industrial chemicals in collaboration with Prof Pim de Voogt and Dr John Parsons from UvA. The applied research institutes Deltares, TNO, WFBR, and KWR bridged science to application and vise versa.

Water Nexus was granted by NWO Perspectief and started in 2015, with a budget of 6.6 Million Euro (2.9M by NWO, to which the Ministry of Infrastructure and Watermanagement added 1.5M, and 2.2M was financed by the other partners). The research results of 15 PhD's, two postdocs, their supervisors, and partners involved, is presented here to you. We hope you will enjoy and learn a lot, and get inspired to join us in striving for a sustainable and climate robust water provision for industries world-wide.

Prof. dr. Huub Rijnaarts,
program coordinator

Colofon

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Societal relevance

Worldwide, delta areas are of immense economic importance because of their dense concentration of population, industry and agriculture. Half of the world's population will live in delta areas at the end of this century. The economy of delta areas relies on fresh water: good quality fresh water is essential for public health, food production and industrial activities. Severe scarcity of fresh water in delta areas in the future is imminent due to a growing demand for fresh water and due to saltwater intrusion. Worldwide, the fresh water demand for various sectors is rapidly increasing:

- For agricultural use, the shortage already is more than 100 billion m3/yr.
- For domestic use, a shortage of 50% is forecasted.
- The industrial demand in 2025 is predicted to be at twice the level of the year 2000.

The pressure on fresh water resources from a growing fresh water demand and increasing pollution levels is enhanced by changes in climate, such as extremes in drought and precipitation and rising sea levels, and soil subsidence, resulting in saltwater intrusion.

Present attempts to find solutions for a more robust fresh water supply in delta areas are fragmented, focusing on partial solutions, and are often connected with high costs and poor sustainability. Furthermore, it is clear that these solutions cannot create sufficient fresh water quantities to really solve future fresh water scarcity problems. For a genuine breakthrough, a radically different approach is needed: integral water quantity and quality management. NWO-TTW funded research program Water Nexus developed a coherent set of technologies, tools and models that enables such a breakthrough.

Ambition of Water Nexus

The ambition of the Water Nexus program was to develop integral solutions for problems with water scarcity in delta areas worldwide. The central paradigm shift was to consider saline water as a resource, and not as a threat: saline water where possible, freshwater where needed. Water Nexus focused on large fresh water volume sectors with an emphasis on industry, but in connection to agriculture, horticulture and ecosystems, with a high orientation on impact in solving scarcity.

Water Nexus advocates a paradigm shift in water sourcing and use. Saline water is not treated as a threat but as an opportunity: creating alternative water sources for economic use – saline water as a new economic driver – and protecting essential freshwater resources. To enable the use of saline water as a resource, Water Nexus focused on two critical aspects of water supply:

- *Water distribution control:* control models were developed to create an optimal spatial distribution of saline and freshwater (saline water where possible, freshwater where essential).
- *Alternative sources:* treatment technologies were developed to make saline water suitable for large volume specific applications, such as industrial cooling and agriculture, with minimal costs, i.e. only removing those substances that hinder use, such as monovalent salts, and maintaining substances beneficial to use, such as nutrients in agriculture.

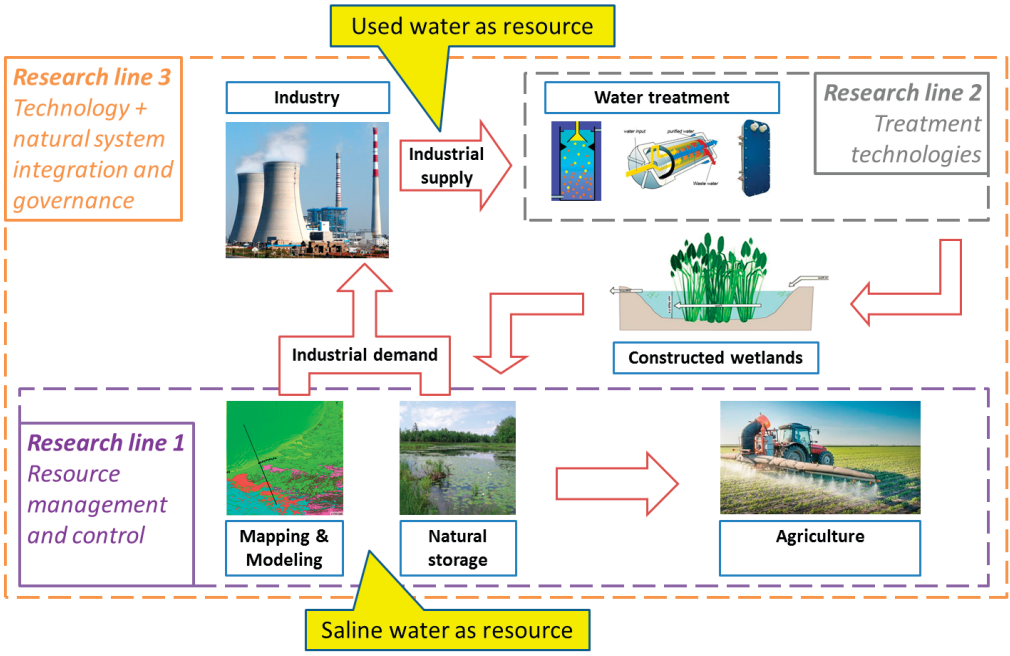
Water Nexus scientific research: Objectives and program set-up

The focus of Water Nexus on different aspects of robust fresh water supply resulted in the design of a multidisciplinary research program that consisted of three interdependent research lines. Its execution required a combination of scientific disciplines, such as geohydrology, soil physics, microbiology, membrane technology, electrochemistry, catalysis and surface science, and systems ecology. This scientific research was performed by renowned research groups at Dutch universities, each of them being recognized for being a leading research group in their field of expertise. The three research lines of which the Water Nexus program consisted were:

- *Research line 1: Resource management:* the focus of this research line was to obtain and maintain an optimal spatial distribution of saline and freshwater (saline water where possible, freshwater where essential) by developing models and control tools for strategic and operational water management. Instead of using scarce fresh water to reach such a distribution – e.g. flushing – saline water is used to push freshwater to critical areas. Special attention was given to salt concentrations at root

zone levels, essential for food production and nature development. Here especially monovalent salts can be detrimental.

- *Research line 2: Treatment cycles of use:* the focus of this research line was to develop treatment technologies enabling the use of saline water as an alternative to fresh water. Sources can be either natural saline water, or water from industrial production, such as from oil and gas production. Technologies are sustainable and cost efficient, removing only those substances that hinder the use of saline water, such as monovalent salts and industrial micropollutants, and maintaining those that are beneficial to the end use.
- *Research line 3: Integral blueprints:* this research line focused on developing integral solutions, combining the newly in Water Nexus developed technologies for optimal use of fresh water and saline water quantities and qualities, integrating the results of line 1 and 2 in a unified approach for water provision of industry and other sectors in a region. Integral solutions and underlying models were validated and tested in simulated and practical cases.



Schematic overview of the design of the Water Nexus research program.

The consortium, at the kick-off of the program at Dow Benelux B.V. in Terneuzen.

2
The Water Nexus consortium

Participants

Key to Water Nexus is that it covered the entire innovation chain: partners involved were universities, institutes for applied research, technology providers, consultants and end users (including Dutch water managers). Water Nexus combined excellence in fundamental and applied sciences with application knowledge from private companies.

Water Nexus consortium partner	Role within Water Nexus	Active in research line
Deltares	Knowledge institute, end user	1, 3
Dow Benelux	End user	2,3
Eijkelkamp	Technology supplier	1
Evides	End user	2,3
Hoogheemraadschap Rijnland	End user	1
KWR	Knowledge institute	1,3
Magneto	Technology supplier	2
Nijhuis Industries	Technology supplier	2
Oasen	End user	2
Paques	Technology supplier	2
Pentair X-Flow	Technology supplier	2
Plant-E	Technology supplier	2
Priva	Technology supplier	2
Ministery of Infrastructure and Water Management	End user	3
Royal HaskoningDHV	Consultant, Technology supplier	2,3
Shell	End user	3
STOWA	Knowledge institute	1,3
TNO	Knowledge institute	1
Wageningen Food and Biobased Research	Technology supplier	2
Witteveen+Bos	Consultant	2
WLN	End user	2,3
Wageningen University	Knowledge institute	1,2,3
Technical University Delft	Knowledge institute	1,2
Technical University Eindhoven	Knowledge institute	2
University Twente	Knowledge institute	2
University Utrecht	Knowledge institute	1
VU Amsterdam	Knowledge institute	1
University of Amsterdam	Knowledge institute	3

End-user contributions essential for 'science with impact'

A common objective of the Water Nexus end-users was to develop solutions for robust future fresh and salt water management in delta areas worldwide. In addition, end-users were interested in more specific research themes, and contributed with their in-house experience to ensure that the scientific research in Water Nexus resulted in societal impact:

TNO

'The subsurface is an important aspect for Water Nexus and within TNO, the Geological Survey of the Netherlands (TNO-GSN) is a knowledge centre of the subsurface. Through the cooperation in Water Nexus, the subsurface knowledge could be expanded to further contribute to a sustainable Netherlands. TNO-GSN contributed with the public information available on the websites DINOloket.nl and grondwatertools.nl and with knowledge of geology and hydrogeology.'

Plant-e

'Support of fundamental research is important for Plant-e since we spun-off from a university ourselves. Our combination of fundamental and practical knowledge could enhance the applicability of the results of the project. Moreover, we were really interested in the results of the desalination work package to see if it would be applicable to our own business as well. We contributed in-kind through knowledge-sharing and making our pilot projects available for the research consortium. In the final stage of the project we started a pilot-study in a wetland with two of the partners to develop our Plant-e system as an early warning system for heavy pollution.'

Nijhuis Industries

'We participated in Water Nexus to gain new knowledge on the application of anaerobic and aerobic granule sludge under (varying) levels of salinity. This knowledge will be used to design more cost effective treatment steps for the treatment of wastewater and de production of process and boiler feed water.' 'Furthermore, the Water Nexus could give us new solutions to treat and re-use brackish and/or salt water in the Food, Beverage, Dairy, Textile, Pharma, and Oil and Gas industry. We were actively involved in Research line 2.1: Biological nutrient

removal following and discussing the research on both anaerobic as well as aerobic granular sludge treatment of high saline wastewaters. Furthermore, we incorporated knowledge of this research in a process design of a treatment for industrial wastewater of high salinity, which was made alongside the project Water Nexus.'

Pentair X-Flow

'Pentair X-Flow is the world leader in ultrafiltration capillary membranes and additionally manufacturer of microfiltration and nanofiltration capillary membranes. Typical applications of these membranes include the (pre)filtration of potable water, waste water and beverages, such as wine, beer, milk and cider. The Water Nexus program has interesting synergies with Pentair X-Flow, in finding a balance between the supply and demand of salt and fresh water for municipal and industrial markets. Newly developed capillary membranes based on current Pentair X-Flow membranes can definitely provide a safe, sustainable and affordable production method for potable water.'

Dow Benelux B.V.

'Dow strives to reduce its water footprint by enhancing internal water recycling and eliminating the use of virgin fresh water from external sources. Dow wants to achieve these objectives by collaborating with external parties, optimizing regional water management, and applying innovative technologies, such as wetlands for the treatment of miscellaneous brackish water streams. Dow participated in the research lines on the removal of sodium and micro-pollutants from saline water enabling re-use and on the line addressing Integral Blueprints, providing practical data and expertise on streams and infrastructure. Real industrial water samples were provided to execute lab and pilot scale tests to develop suitable treatment trains for the reuse saline process water streams. On a regional level, support was given for developing suitable models for infrastructure scenarios based on practical needs and conditions.'

Evides Industriewater

'Together with our client Dow Benelux in Terneuzen, we are looking for sustainable solutions for industrial water supply in the region Zeeuws Vlaanderen. By using local water sources competition with drinking water sources can be avoided. Use of local water sources, such as reuse of treated wastewater, is an option that is already applied, however water reuse can be increased when treatment technologies develop further. Also treatment of brackish water

sources can contribute to sustainable solutions. In Water Nexus, technologies were developed which make it possible to increase the use of local water sources. Evides Industriewater played a role in 2 research lines: Research lines 2 and 3. We gave input with our knowledge where the role of researcher was done by PhD students. Our pilot location in Terneuzen was available to place a wetland pilot. At the pilot location several water sources were available.'

Witteveen+Bos

'As we are actively involved in the daily challenges of our clients related to fresh water availability, salinity and drought issues, the development of innovative integrated solutions based innovative circular water approaches is the main reason to be involved in Water Nexus. We developed knowledge and expertise on integrated fresh water solutions by interacting with the stakeholders, knowledge institutes, universities and end-users. We conducted result validation and implementation consultancy. By conducting the integrated design courses for PhD's we actively engaged with the experts in the field and developed new insights and business opportunities for our consultancy and engineering services.'

Royal HaskoningDHV

'Water stress is in fact all around the world a challenge of growing concern. We have plenty of saline water but only 3% of our water on earth is fresh water. For that reason we supported the slogan of the Water Nexus Programme: "Saline water when possible, fresh water when needed". If salt water can be used for different purposes, like for agriculture or industry, this opens opportunities for becoming more resilient on water availability. "Enhancing society together" is the slogan of Royal HaskoningDHV and within the consortium we created added value with our knowledge on circular water concepts. As Royal HaskoningDHV, we contributed to two research lines. One was on the use of aerobic and anaerobic granular sludge for the treatment of wastewaters that are high in their salt concentration. With our aerobic granular sludge technology Nereda® we have direct interest in this application. The other one was on the Integral Blue Prints where most of the knowledge gained during the whole Water Nexus program was integrated in design approaches for implementation in practice. Besides, Paul Roeleveld was a member of the steering committee.'

Shell Global Solutions International B.V.

'The main reason to participate in Water Nexus was to explore novel treatment and re-use systems for high salinity water streams in Shell's operations, mainly from produced water

sources. This included mapping of saline/freshwater sources, mapping of water salinity versus crop yields, removal of specific contaminants to allow use of treated produced water in non-food crop irrigation. We contributed to Water Nexus by providing one of two end-user case studies, the treatment of oil produced water from and the potential re-uses in our own operations or in non-food crop agriculture.'

Deltares

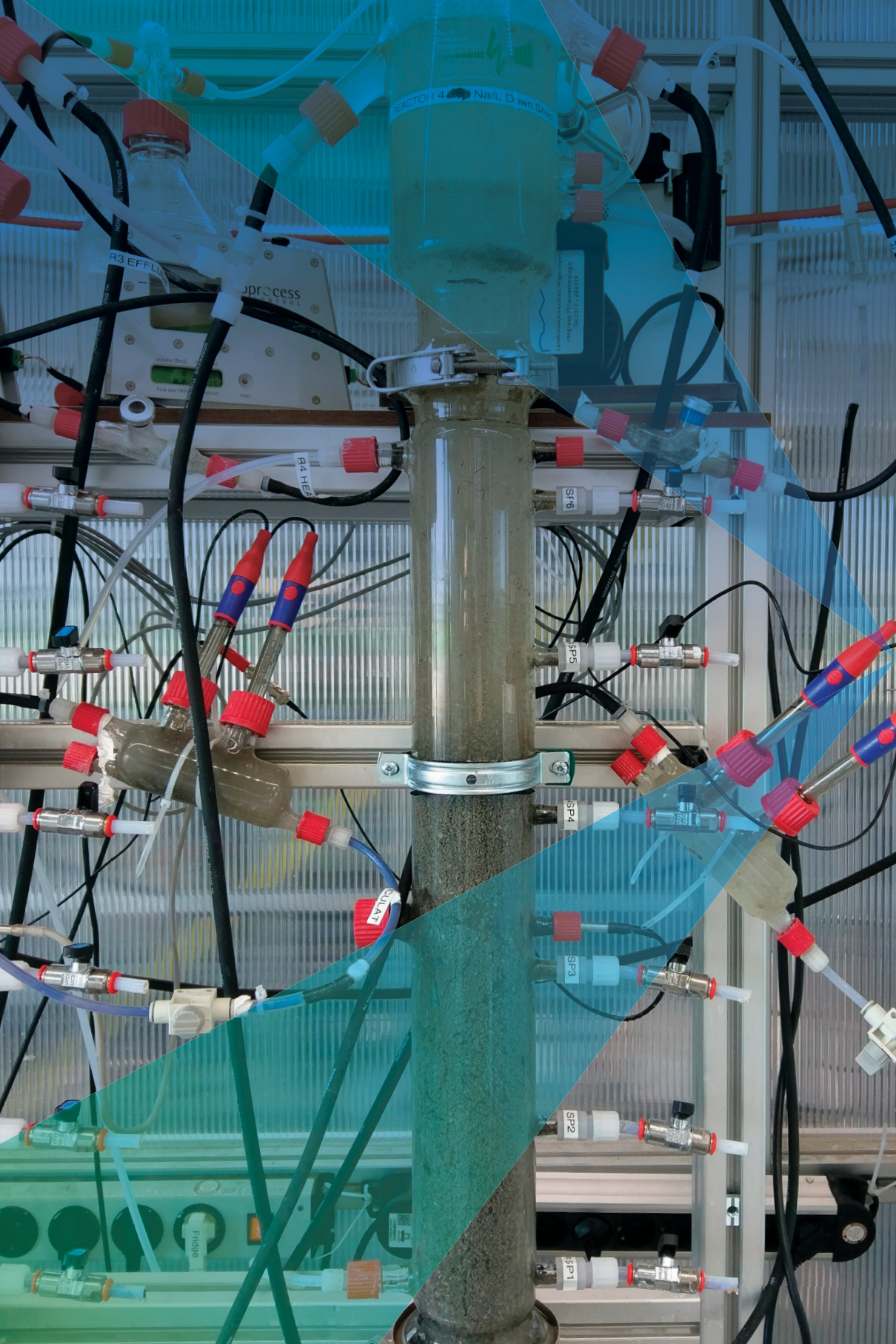
'Deltares was interested in participation in Water Nexus because it matched (at the time) with the scope of our strategic research knowledge programs, in particular the program Fresh water supply in urbanizing deltas. Even now, anno 2021, the Water Nexus programm closely matches with 3 out of 4 of our so-called Deltares missions (viz. Future deltas, Sustainable deltas, Safe deltas). Water Nexus gives us knowledge and tools that contributes to the sound scientific base that we think is needed in our applied research projects, in the Netherlands as well as abroad. Deltares was involved in the research of research line 1.1. All three PhD's in this research line were positioned part-time at Deltares workplaces, where we provided our open source modelling tools, monitoring tools and data.'

KWR Water Research Institute

'Sustainable use of our environment and specifically the management of freshwater resources is an important field of research for KWR. It is increasingly recognized that significant changes in land use and water management are required to balance the future regional freshwater supply and demand. A solid scientific base is required for our work, in which we 'bridge science to practice'. KWR was especially involved in a PhD-research on the impact of salinization on natural vegetation and was part of the User Committee of the project 'Local Operational Water Management and Control'.'

Paques

'The main reason to participate in Water Nexus was the focus on treatment of saline wastewaters. There is up to date still little knowledge whether this is treatable, and under what conditions. We actively participated in the regular progress meetings, and also provided two of our full scale reactors that treat saline wastewater that could be used as a case-study in Water Nexus.'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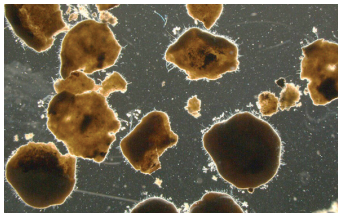
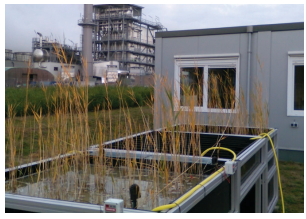
3
The scientific research in Water Nexus: Objectives and researcher experiences

This chapter provides an overview of the objectives of the scientific research in Water Nexus per research line, provides by the research line leader.
The PhD-researchers that performed the scientific research in collaboration with their university supervisors and external collaborators will present the highlights of their research project, their recommendations for future application of their outcomes and future study directions.



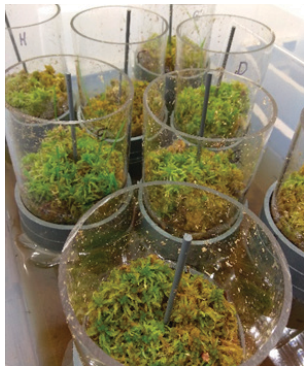
A microscopic picture of granules – flocks of microorganisms – used for the treatment of saline industrial wastewater, as studied in research line 2.1.



Pilot scale constructed wetlands at location of end-user Evides Industriewater, including plant microbial fuel cells, as studied in research lines 2.3. and 3.

Drone used for monitoring polder flushing, as performed in research line 1.1.

A picture of the helicopter that was used to obtain airborne electromagnetic measurements in work package 1.1.1.



Laboratory-scale plant experiments with plants from the field, as studied in research line 1.2.

Picture of severe swell-shrink related soil degradation in a sodic soil, as studied in research line 1.2.


1.1

Research line 1.1
Resource analysis and regional water management

Prof. dr. Marc Bierkens, Utrecht University

Objectives

The focus of research line 1.1 was to develop models and techniques that enable strategic and operational water management, resulting in an optimal spatial distribution of saline and freshwater, on a regional scale. The project consisted of three parts:

- assessment and monitoring: where can fresh and salt water resources be found?
- scenario analysis and structural adaptation: what will be the development of salt and fresh water resources in the future, how can we adapt and what will be the effectiveness of new technologies?
- operational management and control: how can the system be optimized on a day-to-day basis?

Based on these three parts the following work packages (WPs) were defined

- *WP1.1.1. Rapid regional mapping of salt-fresh water distributions:* combining airborne geophysical data and (a minimum of) earthbound data with density-dependent flow models for accurate monitoring and prediction of the fresh-salt water spatial distribution and related hydrogeological properties.
- *WP1.1.2. Rapid modelling and scenarios for strategic policy development:* developing a toolbox for quick and comprehensive fresh-salt water model construction and scenario development, enabling identification of vulnerabilities and opportunities for water distribution control, and the robustness of the water system against autonomous and anthropogenic changes.
- *WP1.1.3. Operational management of regional salt-fresh water resources:* integrating forecasts on weather and water transport into models for prediction-based optimal control of regional fresh-salt water distributions.

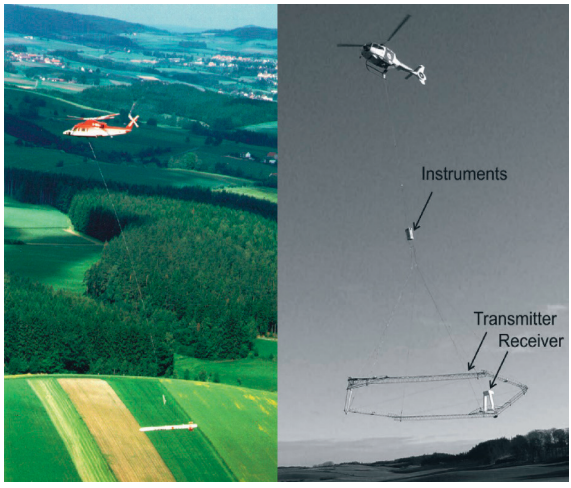
Rapid regional mapping of salt-fresh water distribution

Jude King, Utrecht University

Mapping groundwater salinity and hydrogeological properties using helicopter-borne geophysical measurements

Aquifers in low-elevation coastal zones are a highly important freshwater source for millions of people globally. Unfortunately, these aquifers are highly stressed by human activity and as a result, they suffer from salinization. Consequently, it is important to understand the distribution of fresh or saline groundwater to inform effective groundwater management strategies. I studied the use of airborne electromagnetic methods (known henceforth at airborne EM) as a tool to map this phenomenon. The method works by suspending an instrument beneath a helicopter that emits electromagnetic signals, a response is then recorded which relates to the locations and depths of groundwater salinity and lithology. An airborne EM survey typically flies at about 150km/h with an instrument altitude of around 50m above the ground. Surveys are flown in a tight grid pattern (generally only a few hundred meters apart), measurements are typically taken around every 4-5m along the flight paths.

'Airborne electromagnetic methods are a rapid and efficient way to map groundwater salinity'



Picture of the helicopter that was used for airborne electromagnetic mapping.

For my research I studied the sensitivities of airborne EM mapping methods, as well as developing improvements to improve overall accuracy and mapping ability.

The results of my research effectively answer the following questions:

- How does the processing of airborne EM data affect mapping accuracy?
- What novel methods can we use to improve processing?
- What is the most cost-effective way to plan a survey given the area and availability of data?
- How can we simultaneously map salinity and hydrogeological (e.g., hydraulic conductivity) properties?

'Careful processing of airborne data is highly important for good mapping accuracy'

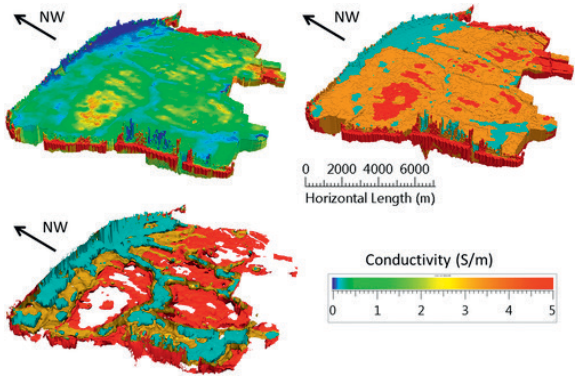
An example: Quantifying the use of ground-based data to complement airborne surveys

Airborne EM surveys are not only sensitive to groundwater salinity, but also to the lithology of the subsurface. A result of this is that additional ground information is needed to split the measured signal between groundwater and lithology. The amount of lithological information required for accurate mapping is unclear, due to the heterogeneous nature of the subsurface. As obtaining ground-based information is expensive, it is important to understand the added value of it. As a result, I conducted a large-scale 3D synthetic study to test different configurations of flightline spacing and 'acquired' ground data. Results of the study concluded that economically, the most important factor to consider is a careful processing of airborne EM data rather than an intensive collection of ground data. The results are potentially good news for data-poor areas, as accurate mapping can be achieved with relatively little ground data.

'It is possible to estimate hydrogeological properties of the subsurface by flying repetitive airborne surveys'

Airborne electromagnetic surveys are sensitive to groundwater movements over time

Due to human activities *and* natural causes, the locations of fresh and saline groundwater can change over time. Using 3D groundwater modelling techniques, I showed that this movement is sensitive to airborne EM measurements. As a result, it was also possible to calculate the length of time needed between two surveys to successfully map these changes.



Example of groundwater electrical conductivity data obtained by airborne electromagnetic mapping.

As groundwater movements are affected by hydrogeological properties (e.g., hydraulic conductivity and porosity), I used these two 3D models (over the same are at two points in time) to estimate several hydrogeological parameters. The results are potentially useful for the difficult task of parameterizing groundwater models, which are also used to inform groundwater management strategies.

'An accurate map of groundwater salinity can help improve groundwater management strategies – and thus allow greater self-sufficiency.'

Airborne EM can contribute to groundwater management in water-stressed regions worldwide

In water-stressed regions such as low-elevation coastal zones, simply having an accurate map of groundwater salinity can help improve groundwater management strategies – and thus allow greater self-sufficiency. Of course, airborne EM is a convenient way to do this. As a result, my earlier research focused on practical understanding of the method – as well as highlighting methodological improvements. The outcome is a 'user manual' of sorts, where regional stakeholders can plan and execute these surveys in a well-informed manner. The latter part of my research examined longer-term water management (over many years) – where the use of flying repeated surveys was investigated.

The future: Coupling airborne EM data with groundwater modelling

I would recommend that more advanced optimization and computing methods are applied to coupling airborne EM data with groundwater modelling. While my research highlighted the potential of flying repeated surveys to recover hydrogeological properties, there was a processing bottleneck where the resulting models were over-simplifications of reality. Solving this would allow highly heterogeneous models over large areas and therefore help improve long-term groundwater management strategies.

Model predictive control of water level and salinity in coastal areas

Dr. Boran Ekin Aydın, Delft University of Technology

Flushing low-lying polder systems with fresh water to prevent salinization

During my research, I focused on control of the surface water system in coastal areas, which are affected by saline groundwater exfiltration. In low-lying delta areas such as the Mississippi delta in Louisiana (USA), the Ganges-Brahmaputra delta (Bangladesh), or the Rhine-Meuse delta (The Netherlands), polders experience surface water salinization problems due to saline groundwater exfiltration, which is the upward flow of saline groundwater from the subsurface. A significant increase in surface water salinization is expected globally driven by rising sea levels, leading to a decreasing freshwater availability. Land subsidence, climate change induced decrease in precipitation and sea level rise are expected to accelerate salinization of groundwater and surface water systems.

'The main focus of my research was monitoring and control of a real low-lying polder with a problem of salinization of the surface water system.'

To counteract surface water salinization, freshwater diverted from rivers is used for flushing the canals and ditches in coastal areas. Sustaining freshwater-dependent agriculture in such areas will entail an increased demand for flushing, while the demand of a better water quality will tend to increase. On the other hand, freshwater usage is not explicitly considered for polder operation and results in excessive use. Decreasing the amount of freshwater usage for polder flushing can create additional supply opportunities for industrial users, drinking water companies or other irrigation systems.

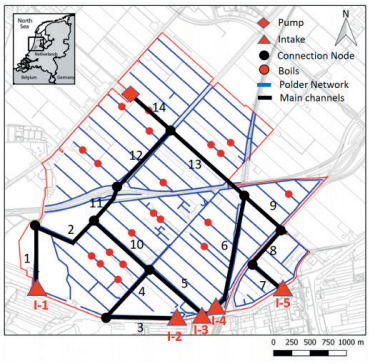
For a real polder network, open research questions on "how to optimally monitor and control salinity?" existed and had to be addressed. Therefore, in my research I focused on monitoring and control of a real low-lying polder with a problem of salinization of the surface water system. I aimed to better understand and control the surface water salinity and quantity in low-lying polder networks using Model Predictive Control by explicitly considering the amount of freshwater used.

Lissertocht Catchment: A low-lying Dutch polder as a test case

On the first day of my PhD, I had a field trip to the Lissertocht Catchment, which is located approximately 25 km southwest of the city of Amsterdam. The Lissertocht catchment is a representative deep polder in the Netherlands with saline groundwater

exfiltration problems. This polder has been used by different researchers to better understand and model the saline groundwater exfiltration dynamics. On top of these studies, during my research, I focused on the monitoring and control of this polder and for the development and testing of my results I used real field data from this polder. For the complex network of channels, I designed an optimal salinity sensor network, which can be used by the Model Predictive Control scheme I developed for the same polder.

'A representative Dutch polder, Lissertocht catchment, is used to develop and test the optimal monitoring and control schemes I developed.'



Location of the Lissertocht catchment (top left) and the layout of the controlled network of the main channels (14 in total with 9 connection nodes), intakes (labeled as I-1 to I-5), pump station and the boils in the area as used in my research.

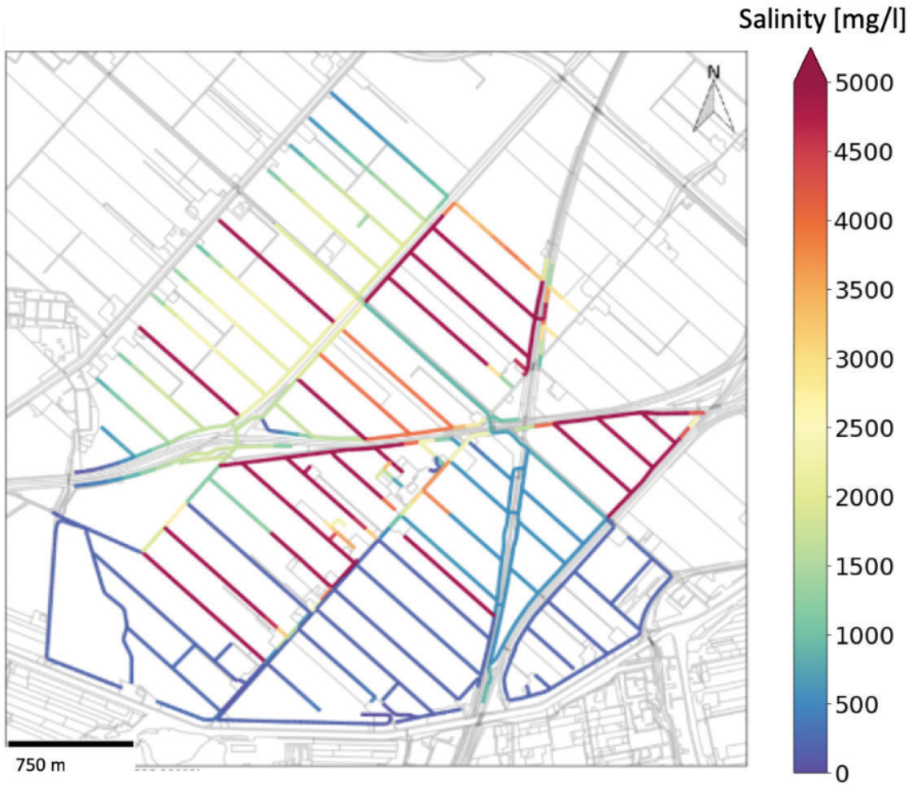
Real time measurements allow real time control of the salinity in polder surface water systems

The motto of Water Nexus project was to use freshwater only when it is necessary! I think the most remarkable result of my research is in accordance with this motto. Compared to a reference scenario that uses traditional polder operational rules, using the controller I developed, we showed that up to 45% freshwater can be saved. We achieved this, by using detailed physically based models for the controller and tested it (simulations) in a real polder network using real saline exfiltration data. In addition to the freshwater savings, our approach results in reduced pumping that will decrease the total energy usage of the pumping stations. Real time control of the polder is possible with real time measurements. Another important part of my research was the optimal placement of salinity sensors. We followed a generic optimization method and showed that only three salinity sensors were enough to monitor the complicated salinity dynamics in Lissertocht catchment.

'Up to 45% freshwater can be saved by the model predictive control scheme developed!'

Global application of the model predictive control scheme to decrease fresh water use: Economic model predictive control

I am very proud to state that the Model Predictive Control scheme and the monitoring network placement optimization method are not case specific and can be applied to anywhere in the world. Our approach will decrease the total freshwater usage of an operational polder system, while satisfying the salinity and water quantity constraints of the system. My research did not consider the real economical value of the operation of the polder (including flushing, energy used, damage to crops, revenue of the cultivated crops). By combining the economy of the process and the performance, together with an economic objective function and formulating an Economic Model Predictive Control (EMPC) scheme, it is possible to achieve an economical and sustainable management of polder networks.



The spatial variation of surface water salinity in the Lissertocht catchment, Haarlemmermeerpolder.


1.2

Research line 1.2
Local operational water management and control

Prof. dr. Sjoerd van der Zee, Wageningen University & Research

Objectives

Project 1.2 focussed on operational management and control at a local (farm) scale to ascertain water availability of good enough quality. In view of the focus of Water Nexus, the impact of salinity was of main interest, but in addition, soil structure degradation as caused by salinity was also considered in detail, as such degradation can be practically irreversible. The research was organized in several main tracks that concerned:

- Management of ground water in coast-adjacent fields with upwelling salt water.
- Assessment of the impact of salinity in terrestrial (fresh water) ecosystems.
- Cross sectorial use: sustainability of use of marginal water and effluent.
- Upscaling of fundamental understanding of sodicity on soil structure degradation.

The research was organized in three work packages

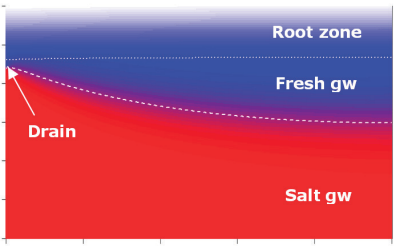
- *WP1.2.1. iDrain – Anticipating drainage systems in salt affected lowlands:* Develop understanding and model tools that aim at optimal water storage by intelligent drainage management. Account for the presence of fresh groundwater overlying saline or brackish groundwater in the adaptable drainage concepts. Develop instruments to enable adaptable drainage operation under erratic rainfall and irrigation strategies.
- *WP1.2.2. iNurture – Stabilise existing salt-freshwater distributions and limit temporal variations:* Monitoring and modelling of various nature (development) sites to support water level management that allow stable salinity gradients under erratic weather conditions. Experimental salt tolerance assessment and the eco-physiological mechanisms thereof for wild plants and agricultural crop species with temporary salt stress. Adjust soil-water-plant model platform with improved plant salt tolerance functions (WP1).
- *WP1.2.3. iRe-use – Economizing marginal (waste) water:* Develop an integrated risk analysis methodology of re-use of effluent and marginal irrigation water for agriculture. Illustration of concepts towards CEC (contaminants of emerging concern). Upscaling of sodicity theory to induced soil structure degradation.

iDrain
Anticipating drainage systems in salt affected lowlands

Daniël van de Craats, Wageningen University & Research

Use of controlled drainage systems to limit impact of drought and salinity

Averaged over the year, we are privileged with a precipitation surplus in the Netherlands. However, during the growing season, we may still experience water shortage due to high evaporation rates and low precipitation amounts. We have seen plenty of examples over the last few years of withering crops, but also of local but intense summer rain storms pouring down a lot of water at once. This research is about using controlled subsurface drainage systems (in Dutch: regelbare drainage systemen) to anticipate on coming (weather) events. With these controlled drainage systems water can be retained in a field by raising the drainage base of the drainage system when little precipitation is expected, and water can be discharged when the soil becomes too wet. By correctly anticipating on future events we can improve the availability of fresh water in agricultural fields.



Schematic picture of the effect of using controlled drainage on the fresh and salt groundwater distribution.

In salt affected lowlands, an extra complicating factor is the presence of brackish or saline water in both surface waters and shallow groundwater. When these salts move into the root zone, either via irrigation (on the surface or via drains) or through capillary rise of shallow groundwater, crop growth might be hampered in multiple ways. Luckily, in the situation of brackish groundwater, pockets of fresh water can be present in between the drains. These rainwater lenses harbor a viable source of fresh water for crops. Focus of drainage base management in these situations should therefore be on maintaining or expanding these lenses whenever possible to limit the risk of salt entering the root zone in dry periods.

Our focus was on developing an algorithm to model groundwater levels and thickness of rainwater lenses simultaneously, as function of drainage base management and weather forecasts. The algorithm not only models these, but also finds an optimal strategy for management of the drainage base for the near future based on (a selection of) several criteria including:

- Optimal and threshold water levels
- Rainwater lens maximization
- Salt discharge
- Allowable risk of draining too little - or too much water

The algorithm is based on a combination of (semi) analytical solutions to flow problems, which require little and easy to obtain input data, and are relatively fast to resolve even on a basic pc. This avoids computationally demanding and experience requiring numerical models, making it suitable for everyday use by inexperienced users. It also makes it possible to estimate the effect of forecast uncertainty on predicted water levels.

'Controlled drainage systems can be used to increase water availability – while at the same time limiting risk of salinization.'

Picture of the effect of salinity on the soil structure.

Impact of salinity (and drought) on soil and crops

As a side-step, we also looked into the effect of salts (ions) on soil structure. We found that soil structure can be severely affected under certain combinations of clay composition, ionic composition of the shallow groundwater, seasonal precipitation deficit and sudden fresh water inputs. Although these specific conditions are currently not met in the Netherlands, they can be found in other (deltaic) regions around the world. In such situations, controlled drainage systems might prove very effective in avoiding soil structure degradation.

Anticipation on future events is possible..

We made an extensive comparison between our semi-analytical model and a density dependent numerical flow model. The agreement between the two was very good, with a few centimeters deviation at most. Compared to the effect of uncertainty in for instance soil physical parameters as saturated hydraulic conductivity, these results give confidence in our model. Unfortunately, despite a lot of effort, we were not able to verify our prediction algorithm under real field conditions.

'Special attention to the design of controlled drainage systems is required for optimal functioning.'

But efficiency highly depends on drainage system layout

One of the things which can be clearly demonstrated with the algorithm is that the effect of using controlled drainage systems for everyday use is severely constrained by the

design of the drainage system. Most storage potential is achieved with deeply installed drains. Daily management however also requires that groundwater levels midway between two drains respond reasonably fast to changes in the drainage base – hence drains should be situated close to eachother. In regular (i.e. non-controlled) drainage systems, this combination always resulted in over-drainage and water shortage in the growing season, but this is not the case for controlled drainage. Off course, there is a tradeoff between investment costs (more and deeper drains are more expensive) and potential harvest loss due to water or salt stress.

Picture of an anticipating drainage system in the field.

Broader application of control drainage systems

The application of controlled drainage systems is dependent on local circumstances. We specifically focused on regions with a seasonal precipitation surplus and upward seeping groundwater – conditions which we do not find in most of the inland fresh water-stressed regions. Hence it is not generally applicable – but there certainly are much more deltaic regions similar as in the Netherlands where anticipating with controlled drainage will prove useful. Noteworthy is soil structure degradation due to shallow saline groundwater. In regions where this effect might occur, it is of utmost importance to be ahead of these problems. Once structure degradation has occurred, it proves nearly impossible to reverse the negative effects on crop growth and water infiltration. Prior to degradation, measures as drainage (perhaps with controlled drains) and leaching will likely prove effective in mitigating problems.

Future study directions

We have demonstrated that these anticipating controlled systems are possible – in theory. A field study, in which the algorithm is tested and verified is required to gain experience and confidence in anticipating controlled drainage systems. With that, also attention should be given to costs, potential profits and to farmers motivation to use such systems.

iNurture
Stabilise existing salt-freshwater distributions and limit temporal variations

Milou Huizinga, Vrije Universiteit Amsterdam

Assessment of the impact of salinity in terrestrial surface water related ecosystems

The focus of this project was to assess whether brackish and slightly saline ground- and (sub)surface water can cause salt stress related problems in terrestrial surface water related ecosystems. The current limit for fresh water in The Netherlands is set to 300 mg Cl/L, a threshold determined based on species richness of the aquatic environment. However, this limit is under pressure due to climate driven sea water intrusion and natural fresh water salinization due to groundwater seepage in combination with anthropogenic factors like extensive groundwater extractions for agricultural practices and drinking water. Agricultural practices in the low-lying polders, like the cultivation of bulbs and fruits, are often brought up as sectors vulnerable to salinization. However, natural ecosystems are also a 'sector' that experiences salinization, but the consequences are less studied. This while in The Netherlands we have a unique fresh surface water related natural landscape consisting of former turf pond extraction sites (e.g. Nieuwkoopse, Vinkeveense and Loosdrechtse Plassen, Wieden, Weerribben), naturally formed pools due to a high water table and flooding events (i.e. Naardermeer) and smaller manmade basins. What can we expect when internal and external inflow water affects the salt concentration of the surface water? Little is known about the ecological effect of low salt concentrations and fluctuations, the interaction between water-soil-plant and the consequences for terrestrial ecosystem services and development. In this project we therefor aimed to explore the effects of slightly brackish surface water concentrations on root zone biogeochemistry and the surface water dependent terrestrial fen plant community.

'Salt peaks in the root zone of floating root mats far exceeded surface water salt concentrations.'

An example: Protected plant communities in floating fen ecosystems experience salt peaks

In order to study how surface water salinization affects terrestrial plant and root zone processes, we followed the salt route through time and space during the exceptionally dry years 2019 and 2020. We went to two floating fen nature reserves in The Netherlands: the fresh 'Nieuwkoopse Plassen' (on average 150 mg Cl/l) and the slightly brackish 'Botshol' (fluctuating from 550 mg Cl/l in winter to 1100 mg Cl/l in

summer). We identified the degree of horizontal and vertical salt intrusion by bi-weekly extracting root zone pore water along a transect from the edge of floating root mats inwards. There were three sampling points at 30 – 60 – 200cm from the edge and four vertical depths at 10 – 25 – 50 – 75cm per sampling location. During summer the salt concentration did not go below 800 mg Cl/l, a concentration unpreferable for salt sensitive plant species. And especially during hot summer days the salt concentrations in the shallow root zone could reach extreme salt peaks of 1800 mg Cl/l, surpassing the surface water concentration. During autumn and winter salt flushed out of the system. This implies that during spring-summer a high salt concentration of the surface water should be avoided, while in autumn-winter it might be acceptable since in this period surface water will not reach the root zone of the vulnerable plant community. We are still working on how these salt fluctuations and peaks might have shaped the plant community structure and functioning through time.

Salinization of freshwater systems needs more attention

Salinization has been connected to agriculture in the largest part of conducted research. In this project we have set an important step to put salinization experiments in natural ecosystems on the calendar too. This cannot be achieved by merely extending methodology and outcomes of agriculture based studies, because in contrast to the monocultures in agricultural fields, salt in a natural environment interacts with a complex plant community and with balanced biogeochemical processes. Also, counter-measurements such as used in the agricultural sector (e.g. irrigating during drought or flushing during increases in salinization) are not in play in natural systems. Plus that will not save fresh water. The plant community is at mercy of the abiotic and biotic environment and thus it is less clear how much deviation from fresh water is acceptable at a certain point.

Fieldwork in the 'Nieuwkoopse plassen' area.

Research set-up to study surface water fed salinization

We studied the effect of surface water fed salinization on two functionally different floating fen vascular plant species and two moss species with contrasting water uptake mechanisms. For this we used a research setup that mimics ground- and (sub)

surface water salinization. The effect of salt on growth and survival of an important ecosystem builder, the ectohydric moss species *Sphagnum palustre*, was limited. The species with active water transport (i.e. hair moss *Polytrichum commune* and vascular plant species *Silene flos-cuculi* and *Myosotis scorpiodes*) experienced negative effects of salt at brackish to slightly saline concentrations that are also measured in the 'Botshol' floating root mats. More studies are needed to predict how salinization affects other key and protected plant species. Additionally the effect on community structure and functioning and plant-soil-salt interactions needs more attention. We do think that treating salt as a toxin can help with method standardization and subsequently regulations. This means that next to understanding the process of salinization we need to add that salt is a manageable toxic and unwanted compound.

'Treating salt as a toxin can help with method standardization and subsequently regulations.'

Unexpected outcome

The extreme salt peaks that we found in the root zone of the floating root mats far exceeded surface water salt concentrations. This might explain why salt sensitive plant species were absent in the brackish floating fen ecosystem or decreased in numbers during the dry years of our study.

Future studies on the impact of saline conditions on nature are required

Around one third of global freshwater bodies can be affected by accelerated rates of salinization, but studies on effects of salinization are underrepresented. With this study we were able to explore which salt concentrations could be acceptable without deteriorating the natural values of an ecosystem. Also we have shown the link between surface water salinity and the terrestrial surface water dependent plant community. We found that nature cannot simply be viewed as undisturbed brackish and salt water storage basins. However, that is given the current nature protection goals, often imposed by legislation. Certain ecosystem functions and biodiversity goals can also be achieved with brackish- and salt tolerant terrestrial and aquatic communities. If and how an ecosystem can make a non-detrimental switch from fresh to brackish conditions needs more research. In order to do so it is important that better integration of water, agricultural and nature goals are organized to balance fresh and brackish water. More research is now needed on how landscape dynamics and ecosystem services develop in a changing climate as a result of water resources of different salt levels.

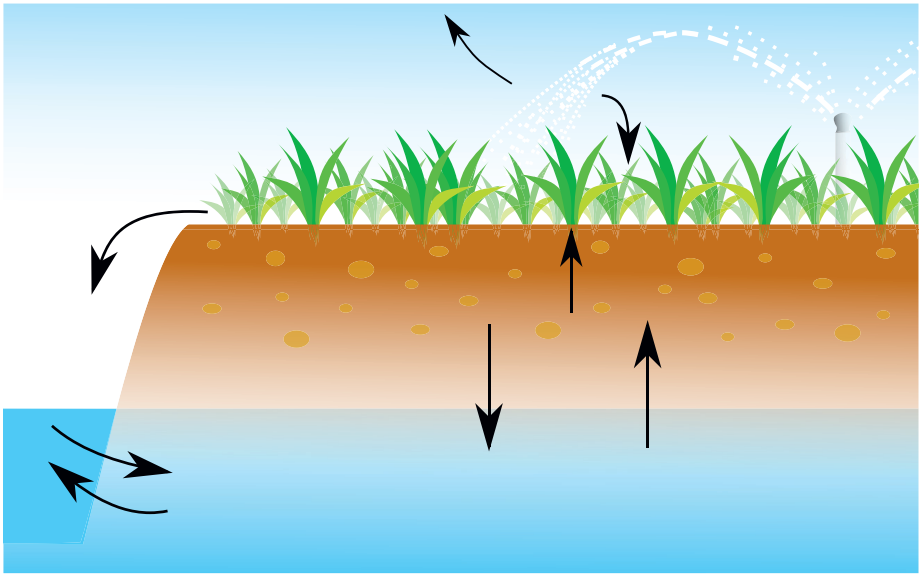
iRe-use
Economizing marginal (waste) water

Pavan Cornelissen, Wageningen University & Research

Re-using wastewater for irrigation

My project focused on modelling the impact of re-using wastewater for irrigation. Wastewater may be re-used for irrigation to save freshwater resources. However, the contaminants present in wastewater may negatively impact the public health and the environment. Depending on its source and treatment, wastewater may contain many different contaminants such as salts, heavy metals, pathogens, and organic chemicals. Contaminants may enter various environmental compartments, such as the soil, crops, or groundwater. The toxicity and behaviour in the subsurface may differ for each contaminant. A framework on how to assess the sustainability of wastewater in an integrated manner does not yet exist. Therefore, the main question we address is:

- How do we develop an integrated sustainability framework for wastewater irrigation?



Schematic overview of water flow in the shallow subsurface.

Soil sodicity

Wastewater often contains high amounts of sodium. When sodium accumulates in loamy and clayey soils, this may lead to irreversible damage to the soil structure. The microscopic clay particles swell at the expense of larger pores, resulting in a denser soil.

This hinders plant root growth and soil water flow. This process is difficult to reverse, and therefore the focus should be on prevention and anticipation. However, there is a knowledge gap in translating the microscopic scale of individual clay particles to effects on the macroscopic parameters such as the hydraulic conductivity. Therefore, we spend a significant part of this project on the topic of soil sodification.

'The prevalence of sodium in wastewater may lead to irreversible degradation of the soil structure.'

We focused on the following research questions:

- Does soil heterogeneity significantly impact the forces driving degradation of the soil structure?
- Can we predict the change in macroscopic soil hydraulic properties (e.g., permeability, water retention) based on the sodium content of the pore water?

Framework for an integrated sustainability assessment

We developed a framework to assess the sustainability of wastewater irrigation in an integrated manner for a given composition of the irrigation water, soil properties and irrigation management which answers the following questions:

- Which contaminants may cause risks to the public health or the environment?
- Which environmental compartments are at risk (e.g., soil, crops, groundwater)
- On what timescale do problems occur (e.g., months, years, decades)

'The sustainability of wastewater irrigation practices needs to be assessed in an integrated manner.'

This information can be used to determine which contaminants should be prioritized for further research, which treatment methods are required, or if the irrigation management scheme should be altered.

Upscaling of soil sodicity effects

In our studies on soil sodification, we found that the heterogeneity in pore sizes plays an important role on the forces that cause soil deformation, as well as the timescale on which these detrimental effects occur. This shows that it is critical to include soil heterogeneity when translating the microscopic sodicity effects to large scale effects that are observed in the field. Additionally, we found that advanced models are capable of predicting at what water composition the soil starts to break down, yielding results which are in reasonable agreement with experimental observations. The critical point

at which the soil structure breaks down depends on both the concentration of sodium relative to calcium, as well as the total salinity.

'The framework can be used to address whether the wastewater is of sufficient quality for irrigation and to identify aspects which should be investigated further.'

The framework is valuable for a wide set of future applications of treated wastewater

Treated wastewater may be re-used for irrigation to decrease the pressure in freshwater resources. While the main application of wastewater irrigation is in agriculture, wastewater may also be used in urban applications, such as the irrigation of parks and sports fields. This research provides a methodology to assess whether the water quality is sufficient for long-term irrigation without leading to problems for the public health and the environment. The framework can be used to identify which contaminants should be prioritized for further research, or which contaminants should be focused on in the treatment process. This also allows to compare the effects of different irrigation management practices. Additionally, the framework also provides information on which parameters should be known with greater precision.

Future study directions

Contaminants of emerging concern

The sustainability assessment framework developed in this project is based on the assumption that environmental quality standards exist for each contaminant. While these standards exist for many contaminants, this is often not the case for so-called contaminants of emerging concern. Much is still unknown about the toxicity and behaviour of many of these contaminants. This highlights the need for more experimental investigations on the properties of these substances.

'Determination of toxicity and behaviour, especially of emerging contaminants.'

Soil mechanics

The coupling between pore water chemistry and soil mechanics is a complex process, in which further steps can be made. Our work on translating soil sodicity effects on the microscopic scale to larger scales is a first step. There is a need for advanced soil mechanical models for the microscopic scale, and adequate upscaling methods in order to obtain a better agreement between model predictions and field observations.


2.1

Research line 2.1
Biological nutrient removal

Dr. Hardy Temmink, Wageningen University & Research

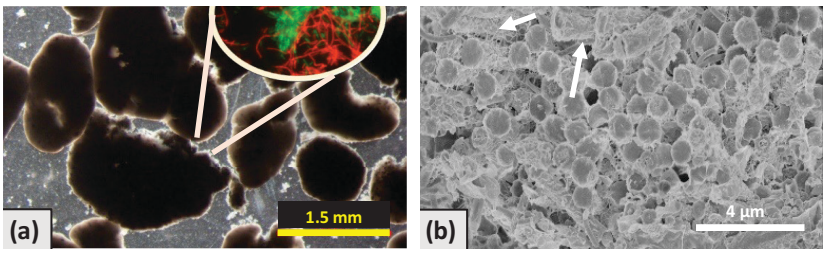
Objectives

Many industries, such as leather tanning, agro-food, petroleum, petrochemical and textile dyeing, generate highly polluted saline wastewater. Preferably the bulk pollutants (usually organic compounds, phosphorus and nitrogen) are removed by a biological treatment process because this is economically and from a sustainable perspective more attractive than physical-chemical treatment. If necessary physical-chemical post-treatment step can further upgrade the water such that it becomes suitable for re-use. In biological wastewater treatment a distinction can be made between anaerobic (without oxygen) and aerobic (with oxygen) processes:

- Anaerobic treatment is most convenient for relatively warm (> 25-30 °C) and high-strength wastewaters because it combines treatment with the production of energy-rich biogas.
- Aerobic processes are more suitable for low-strength and lower temperature (<25-30 °C) wastewaters and if also nitrogen and phosphorus need to be removed.

For both, treatment of saline wastewater presents a challenge. First of all, microorganisms that are exposed to high salinity levels generally have a reduced (treatment) activity because of the high osmotic pressure exerted by the salt. Secondly, for high-rate treatment reactors, i.e. having a small volume, the formation of biomass aggregates in the form of settleable granules is a prerequisite. At high salinity formation of such granules however is difficult. The challenge of research line 2.1 was to tackle both issues, under anaerobic as well as under aerobic conditions. Therefore, research line 2.1 was divided in 2 work packages:

- *WP2.1.1. Anaerobic sludge granulation at highly saline conditions*
- *WP2.1.2. Treatment of high saline water with aerobic granular sludge*



Macroscopy and microscopy images of granules formed during the research in research line 2.1. In (a) morphology of dense, well-settling granules. The insert reveals the different microorganisms clustering within the granule. In (b) a sliced granule showing different microbial morphologies and with the white arrows showing the biopolymer matrix.

Anaerobic sludge granulation at highly saline conditions

Dr. Dainis Sudmalis, Wageningen University & Research

Biofilms for treatment of saline industrial wastewaters

Biofilms are ecosystems consisting of microorganisms clustered in a self-produced, gel-like matrix of biopolymers. Under manipulated conditions biofilms can take a granular shape, which for specialists is known as granular sludge. Granular sludge has an important application in wastewater treatment for converting organic bulk pollutants into valuable chemicals. Due to amongst others, tighter closure of water cycles and increasing agro-industrial activity, in the near future a larger volume of wastewater will become brackish or saline. This has a negative impact on the structural integrity of granular sludge and on the activity of the microorganisms within these granules. For a successful functioning of a compact wastewater treatment plant the structural integrity of granular sludge needs to be preserved. Keeping intact granules is important, because (i) they can contain high numbers of microorganisms – the "workforce" driving chemical reactions to treat the water, which in turn allows to design smaller reactors; (ii) they are heavier than water and therefore can be easily separated from the treated wastewater. High activity of microorganisms is as important as having sludge granules in the reactor, because, as mentioned above, they are the ones driving the conversion of organic pollutants. Our research focused on granular sludge that converts organic chemicals contained in wastewater into methane gas, which can be further used for generation of heat, electricity or both. This type of granular sludge is known as anaerobic granular sludge. The challenge was to form anaerobic granules of sufficient strength and microbial activity to enable treatment of saline industrial wastewaters. The broad questions we wanted to answer were:

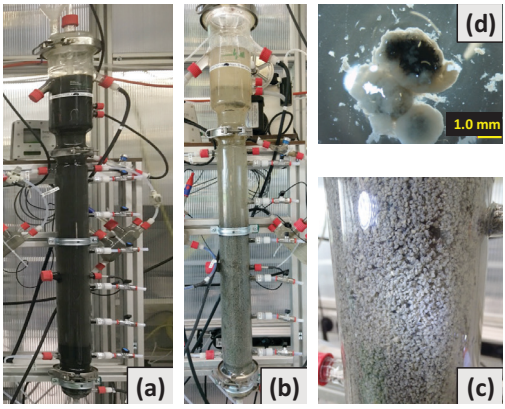
- Can anaerobic granular sludge be formed at salinity higher than that of seawater?
- If and how can we enhance the granulation?
- How can microorganisms within such granules cope with the salinity stress?

'Granular sludge has an important application in wastewater treatment and for converting organic bulk pollutants into valuable chemicals'

Key finding: Fast sludge granulation at salinity above seawater

For the first time, we clearly demonstrated that anaerobic sludge granulation can be achieved at salinities exceeding that of seawater by 40%. This can be achieved provided proper reactor operation approach and source of microorganisms is selected. Under fresh water conditions the process of granule's formation is known to proceed very

slowly: it can take more than 3 months and requires experience from the process engineers to achieve. Remarkably, we managed to grow granules within approximately 40 days despite the extreme conditions the microorganisms were facing.



Bioreactor in (a) before sludge granulation and in (b) after granulation at saline conditions. The granulation in (b) has enabled efficient separation of microorganisms from the treated wastewater. In (c) the distinct microbial granules with the reactor. In (d) a sliced microbial granule revealing a black core surrounded by what seems to be an exopolymer layer.

Key findings: High microbial activity and their adaptation mechanisms to salt

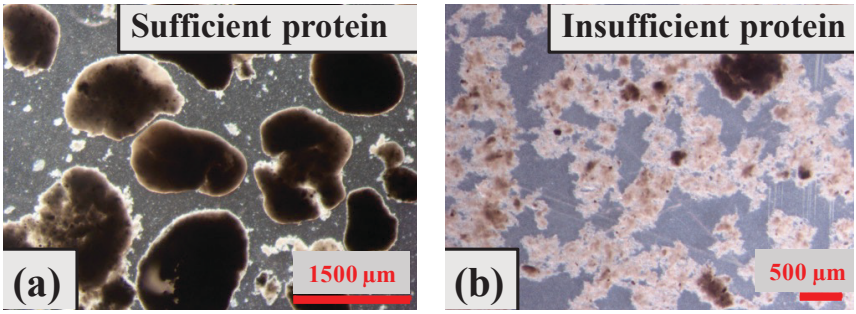
Besides achieving granulation we demonstrated that the microorganisms within our developed granules were sufficiently active to achieve industrially relevant performance, i.e., activity that allows to design compact anaerobic bioreactors. Albeit this high microbial activity was surprising for wastewater treatment systems, in nature an increasing number of anaerobic microorganisms is being discovered that can accumulate small organic molecules within the cells to counteract salt stress. Through further investigation, we discovered that also the microorganisms within our granular sludge could apply such an adaptation strategy. Furthermore, we identified the chemical structure and potential biosynthesis pathways of these molecules, which allowed us to:

- Develop a strategy for enhanced microbial adaptation to salinity;
- Demonstrate that this strategy works by testing it on granular sludge provided from full-scale applications by our industrial partners

Key findings: Proteinaceous substrates enhance the rate of granulation

Many researchers had reported granular sludge disintegration at high salinity. Therefore, a very important question to answer was, what allowed us to achieve the rapid positive results. To answer this, our findings on the microbial adaptation to salt and knowledge of the composition of the polymer matrix in anaerobic biofilms reported by other researchers in the past were the key. We demonstrated that presence of small amounts of proteins in the wastewater significantly enhanced the rate of granulation at high salinity. The explanation for this was that after decomposition (hydrolysis) proteins

can provide the microbes with amino acids, that can serve as biosynthesis precursors or directly for salt stress alleviation. Additionally, the proteins can potentially supply energetically favorable "building blocks" for the gel-like polymer matrix formation, in which the anaerobic microorganisms are entangled as explained above.



Different sludges developed at high salinity. In (a) sufficient amount of protein was present in wastewater and dense, well settling granules developed. In (b) the amount of protein was insufficient, resulting in less dense and poorly settling flocs.

Relevance for water stressed regions

Approximately 5% of the globally produced wastewater is highly saline and this number is expected to increase. The results of our research not only allow to identify saline wastewater streams amenable for anaerobic treatment with granular sludge, but also provide strategies for salt stress alleviation in bioreactors. This in turn supports closure of water cycles through sustainable treatment of wastewaters with increasing salinity. The outcomes of this research are also of high relevance for water stressed delta areas like Hong Kong, where toilet flushing with seawater is already being implemented, resulting in increasingly saline wastewater, treatment of which also involves anaerobic biological processes.

Future research directions

The results of this research project have highlighted several exciting directions for future investigations. Some examples include:

- Studies of chemical properties of exopolymers developed in biofilms under saline conditions, which could lead to interesting commercial applications, such as paper coatings or flocculants;
- Studies of sludge granulation under dynamic salinity conditions, which are relevant for application in practice;
- Investigation if some of the results obtained during this project are also applicable to sludge granulation under non-saline conditions.

Anaerobic sludge granulation under saline conditions: A microbiology perspective

Dr. Cristina Gagliano, Wageningen University & Research

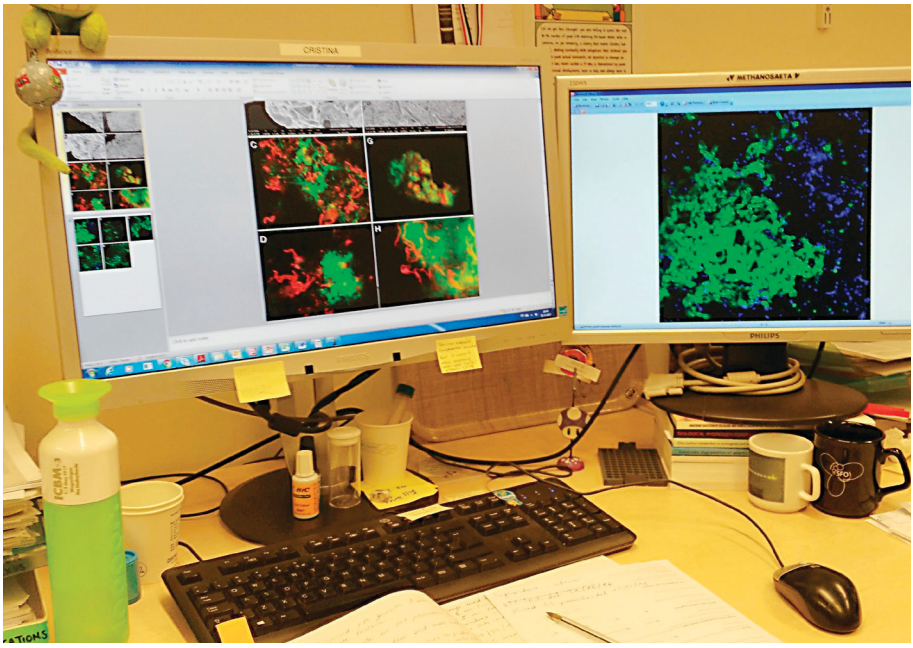
Microbial community structure related to granulation

My research was conducted as postdoc in collaboration with the PhD student Dainis Sudmalis, with the aim to unravel the microbial community structure associated with the formation of sludge aggregates, called granules, during the anaerobic treatment of saline wastewater. Anaerobic treatment of saline wastewater is of interest due to an increase in production of industrial or domestic waste streams. Among the different anaerobic technologies available, we focused on the upflow anaerobic sludge blanket (UASB) reactor, designed in 1970s by Lettinga and colleagues in Wageningen, and commonly applied to treat high-strength industrial wastewaters. In such reactors, microbial biomass spontaneously aggregates into granules with a characteristic structure, and this enables high organic removal and methane production rates. Because of a successful biomass immobilization and retention, the UASB is a good technology to deal with salinity, an extreme environment to which microorganisms often don't acclimatize, causing biomass washout and process failure. For this reason, previous research on this topic was showing granules disintegration, making the anaerobic saline water treatment a challenge.

In our research we investigated the ability of a biomass already acclimatized to salinity (≈ 8 g/L of Na^+) to form granules at different salt concentrations (up to 20 g/L of Na^+), looking not only at the changes in the microbial population in time, but also at the fine structure of the granules formed in different conditions by the same start-up biomass. A complex multidisciplinary approach on the basis of several techniques (in the picture, my work with fluorescence and confocal laser scanning microscopy), allowed us to produce a unique and unprecedented series of research papers on a topic that was often underrated from a microbiological point of view.

Key microbial species for granulation at high salinities: *Methanosaeta harundinacae*

My research was conducted in parallel to the running of many UASB reactors, where it was demonstrated that granules formation was possible (from an acclimated biomass) at salinities from 5 to 20 g/L of Na^+, without hampering the process performances and thus the microbial activity. By utilizing 16S rRNA gene based phylogenetic methods, it became clear that the dominant methanogen was *Methanosaeta harundinacea*, an acetate-utilizing archaeon known to improve granulation, but never reported to be able to grown at high salinity. The structure of granules was dominated by clusters of this microorganism, constituting the aggregation nuclei on which several bacterial subspecies were developing.



Colorful visuals as a result of different microscopy techniques.

The microbial community dominated by *M. harundinacea* produced high amounts of extracellular polymeric substances (EPS), an organic polymer rich in polysaccharides and proteins that creates and hydrogel matrix and favors microbial self-aggregation. Via the application of fluorescent probes targeting the specific cells present in granules, the surrounding EPS molecules (see figure) and Na^+, we discovered that a high amount of mannose-rich EPS was produced by *Methanosaeta*-like cells, and that cells surrounded by such EPS structures were not accumulating Na^+. This was due to the Na^+ binding property of EPS, which was further demonstrated in a study showing the ability of this EPS to work as a cation exchange membrane. Moreover, this EPS was repelling chloride anions, which are also toxic for the microbial community. Since the production of this EPS was stimulated at high salinity (20 g/L Na^+) rather than at low (5 g/L Na^+), the salt concentration was considered a trigger to produce a certain kind of extracellular glycoconjugates. Thus, the excreted EPS had the double role of promoting granules formation, and protect the microbial community from osmotic shock or oxidative stress related to high cations/anions intake. Finally, a metagenomics based study in collaboration with University of British Columbia (Canada) demonstrated that in our reactors we cultivated a new *M. harundinacea* subspecie, with the ability to grow at high salinity thanks to a series of genomic features typical of halotolerant and halophilic microorganisms, that makes it able to survive at high ionic strengths.

Considerations for future application of anaerobic granular sludge for the treatment of saline wastewater

The merged findings of my research and the one of Dainis are a milestone in the field: we do know now that is possible to apply anaerobic granular sludge technology to treat saline wastewater, but a special attention has to be given to the microbiology of the start-up inoculum. An initial characterization of such inoculum can give useful information on its applicability to treat saline wastewaters with certain features. Relative to the characteristics of the wastewater we want to treat, the most important thing to take into account is perhaps the range of salinities that the microorganisms can deal with. Indeed, often salinity fluctuations in such wastewaters are really common, thus they don't have always the same salt concentration. How to approach this? A variegate, halophilic community (they like salt, but it is not essential for their growth), as we found in our work, can be the right choice, and to follow the evolution of the community during time can help to find the right parameters to keep the process ongoing. Indeed, the utilization of a strictly halophilic microbial community (meaning microorganisms which always need salt for their growth) is not advisable, as a low salt concentration would negatively affect the overall process. Thus, this would be exactly the same problem as when we try to expose a non-saline biomass to low concentrations of salt.
If not possible to find the right (halophilic) biomass, it is of importance to plan in time an acclimation period of a selected start-up inoculum in accordance to the wastewater characteristics. For this acclimation period, it is of importance at least to pick-up a microbial community which was already exposed even to low salts concentrations (between and 2 and 5 g/L Na^+ roughly). After all, you will have a stable inoculum which will allow to produce energy (in the form of methane) while reducing organics in the saline wastewater, increasing the possibilities for its reuse.

Microbes first!

I would recommend to study more the characteristics of the EPS produced under certain (saline) conditions and how these features can influence later on the kind of aggregates and their stability within the anaerobic system. Different microbial communities indeed can produce different sorts of EPS, which can then turn in different aggregation behaviors (i.e. a biofilm instead of a granule). On the basis of these characteristics, anaerobic systems different than UASB reactors (such as biofilm- or fixed bed- reactors) can then be studied more in depth for their applicability for saline wastewater treatment. Therefore, overall the recommendation is to always make choices or improvements by looking at the microbial community first. There is a lot to unravel, your microbes will show you the path.

Treatment of high saline water with aerobic granular sludge

Dr. Danny de Graaff, Technical University Delft

The effect of seawater on aerobic granular sludge

An increase in the use of saline water will lead to an increase in salinity in domestic wastewater systems. This can be detrimental for biological wastewater treatment, possibly leading to increased pollution in the environment. In order to anticipate on the effects on biological wastewater treatment, studies are required to assess its impact. My research focused on the effect of seawater on aerobic granular sludge (AGS). Aerobic granular sludge is a novel treatment technology in which multiple contaminants can be biologically removed in a single process step. In this way, organic carbon, nitrogen and phosphorus can be degraded by a mixture of bacteria that grow naturally into spherical granular sludge. The overall question of my research was: "How does long-term exposure to seawater affect the AGS process?"

Aerobic granules for saline water treatment.

Key finding: No differences between seawater-based systems and freshwater-based systems

Removal of phosphorus and organic carbon can occur successfully in seawater. We obtained good removal of organic carbon and phosphorus in our seawater-based system. The rates of removal were even similar to freshwater-based systems. Organic carbon was completely removed during feeding and phosphate was completely removed after aeration. Apart from the biological performance, the physical strength of the granules was also maintained at higher levels than freshwater-based granules.

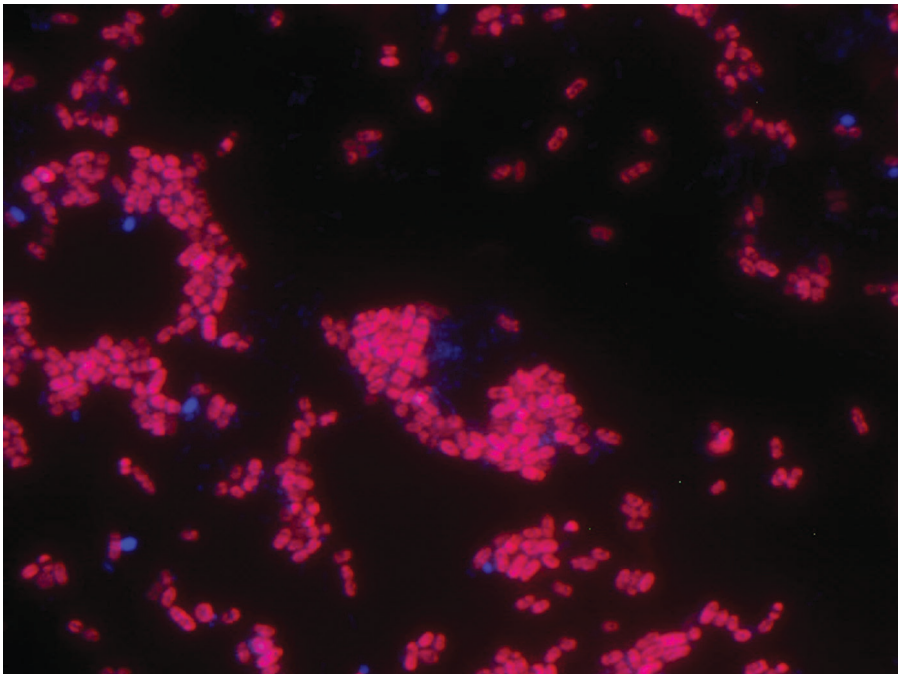
An important factor for real-life performance is the effect of non-saline rainwater in a saline environment. A sudden shock of decreased salinity into the wastewater treatment plant can be negative for the process performance. The impact of such an event is important to assess. We simulated rainwater events by replacing the seawater-based influent by freshwater-based influent. Incomplete removal of contaminants was observed during one cycle, but this recovered completely during the subsequent cycle.

The same bacteria are responsible for both freshwater removal and seawater-based removal

Seawater and freshwater environments are very different for bacteria, so different kinds of bacteria usually thrive in different salinities. We however found that our phosphate-removing bacteria are the same species in both freshwater and seawater-based environments. We dove deeper into the mechanism behind this and discovered the presence of the organic compound called trehalose. This compound is a type of sugar, that can be accumulated inside bacteria to handle higher salt stress. The existence of this compound gives novel insight into the fundamental aspects of salt adaptability.

The granule polymers adapt to coping with seawater salinity

The granular sludge consists of bacteria that are embedded in a mixture of polymers. These polymers are biologically produced by these bacteria and can adapt their properties to their surroundings. Higher salinity gives more stress than freshwater, so coping mechanisms have to be developed. We discovered a novel sugar group (sialic acids) that is present on the outside of these granules. This discovery greatly contributes to the overall understanding of bacterial adaptation to salinity; not only be intracellular molecules, but also by extracellular polymers.



A microscopy picture to determine the content of an aerobic granule.

Adaptation of bacteria allows biological treatment of wastewater in saline regions worldwide

Adaptation of bacteria to seawater-based water systems can occur naturally. An important outcome is the adaptability of bacteria to high salinity. Many bacteria that commonly occur in wastewater treatment plants cannot handle high salinity levels. However, we found that adaptation of the microbial community can occur successfully. Water-stressed regions can therefore still apply biological wastewater treatment processes in their water systems. In this way, these regions can still treat their wastewater and prevent contaminants from entering the environment.

Future studies: Full-scale applicability

This research focused on lab-scale reactor tests, but these results should be upscaled to a full-scale application. There are multiple wastewater treatment plants that are built in coastal regions, where salinity can shift due to tidal events. A more in-depth study should be done on their process performance to find out which factors are crucial for good process performance. The results from this study give a good basis for full-scale understanding.


2.3

Research line 2.3
Removal of sodium and micropollutants

Dr. Thomas Wagner, Wageningen University & Research

Various types of saline industrial water streams are produced all over the world that could be reused to lower the industrial fresh water footprint. These saline industrial streams often contain high concentrations of salts, organic compounds and so-called micropollutants. Research line 2.3 focused on the development of various physical/chemical water treatment processes for the removal of sodium, organic compounds and micropollutants from saline industrial water streams, to allow cross-sectorial reuse. Various individual technologies were studied, while also attention was being paid to the integration of these technologies in treatment trains, also containing natural treatment systems developed in research line 3. The development of these treatment trains allows the treatment of saline industrial water streams for which treatment by only one technology is not sufficient to reach the water quality that is required for reuse. Research line 2.3 consisted of the following work packages:

- *WP2.3.1. New electrode materials for the electrochemical oxidation of saline water.* The aim of this work package was to develop new electrode materials for the electrochemical oxidation of saline water. Important characteristics of these electrodes were assessed, such as the electrode stability, the electrode lifetime and electrode deactivation processes. In addition, process parameters that influence the removal efficiency of these electrodes for organic compounds present in saline water were studied, such as the influence of the salinity, the electrode material, the applied voltage, the current density and the influence of light. A specific challenge was to prevent the formation of unwanted chlorinated transformation products
- *WP2.3.2. The application of the plant microbial fuel cell for sensor applications in saline environments.* This work package studied new types of applications for the electricity generated with plant microbial fuel cells in saline environments, with a focus on optimizing the system for different water streams and plants, characterizing the oxygen and substrate streams in the soil and the effect on the P-MFC and the development of analytical methods to characterize processes occurring in the P-MFC. The plant microbial fuel cell is a fuel cell that utilizes organic matter that is available in wetland systems. Micro-organisms in the anaerobic soil of marshes can convert the organic matter coming from the roots of plants or dead plant material into CO_2, protons and electrons. These electrons can be harvested by placing an anode in proximity of the micro-organisms which is connected through an external circuit to another electrode where a reduction reaction is taking place. By reducing oxygen and protons to water at the cathode, the electrons will flow through the circuit as a result of the potential difference.
- *WP2.3.3. Nanofiltration membranes for the removal of salts and micropollutants.* In this work package, a new membrane generation was developed for the removal

of micropollutants and sodium from saline streams. A new class of nanofiltration membranes was assembled via the layer-by-layer technique, making use of water-based coating solutions. In the layer-by-layer membrane preparation, a porous membrane support is coated by a series of alternating layers of oppositely charged polyelectrolyte (PE) solutions. The influence of steric and charge mechanisms in NF membranes coated with the layer-by-layer technique was studied for two key parameters: the ionic strength of the PE coating solution and the charge density of the PE.

- *WP2.3.4. Technology comparison and integration for the treatment of cooling tower water.* In this work package, various advanced oxidation processes for the treatment of cooling tower water were compared in terms of removal efficiency for organic compounds and micropollutants and the production of unwanted toxic byproducts of advanced oxidation processes. Furthermore, the operational conditions, such as the influence of electrode material, current density, flow rate and salt concentration were assessed. In addition, electrochemical oxidation, nanofiltration, plant microbial fuel cells and constructed wetlands developed in research lines 2.3 and 3 were integrated in a pilot-scale treatment concept for the treatment of cooling tower water and tested with cooling tower water from of the end-users.

Plant Microbial Fuel cell: Mechanistic characterization & application in natural and constructed wetlands

Pim de Jager, Wageningen University & Research

Plant Microbial Fuel cells

The Plant Microbial Fuel Cell (Plant-MFC) is a novel technology in which organic matter is converted into electricity using living plants and bacteria in the soil. Potential applications include electricity production, methane reduction, and nature conservation. The technology therefore addresses different societal challenges such as the global energy transition, water scarcity, connecting remote communities and sustainable food production. The technology can be applied in all (constructed) wetlands or marine environments without harming the ecosystem or altering the aesthetics of the area. And since no external energy storage or input is necessary, the technology can be applied in remote areas without electrical infrastructure, keeping the costs low.

'The Plant Microbial Fuel Cell is a novel technology in which organic matter is converted into electricity using living plants and bacteria in the water-logged soil.'

Pilot-scale Plant-MFC experiment at the campus of Wageningen University & Research.

In my research, I try to understand which underlying processes are responsible for the production of electricity by Plant-MFCs.

- Can Plant-MFCs reduce methane excretion by wetlands?
- How are Plant-MFCs influenced by oxygen excretion from plant-roots?
- Can the plant-MFC be used to power sensor and transmission systems, and can it be used as a biosensor in wetlands?

An example: Plant-MFC sensor system

There is a growing demand for remote sensor systems that monitor wetlands, both natural and constructed. Wetlands are complex systems where plants interact with microorganisms, substrate, the environment, and the water that it is fed with. When any of these parameters change, the performance and removal efficiency of a constructed wetland can also change. This is undesirable if for examples effluent demands must be met. Monitoring the wetlands with temperature, redox and other types of sensors can give an indication of the status of the wetland and therefore the performance. Powering a sensor network with Plant-MFCs means the wetland will effectively monitor itself and will warn the operator that things are changing before the effluent quality is affected.

'The wetland will effectively monitor itself and will warn the operator that things are changing.'

Sufficient energy production for small applications

With a large pilot study, including 100's of meters of Plant-MFCs buried in an outdoor wetland, we showed that the Plant-MFC produces enough energy to power sensoring systems for wetland monitoring. Since this pilot was operated for multiple years, we also obtained seasonal information. This showed that the performance of the Plant-MFC goes down significantly when the temperature drops close to freezing, which is important information when integrating this technology in a wetland. We also found that the electrode material that is used can be simple, very thin and does not need complicated or expensive treatment. This is good news since it will make the eventual product much cheaper and simpler to build. Within the Water Nexus project, the best Plant-MFC system was tested as biosensor in a pilot constructed wetland to further study the feasibility of the Plant-MFC as warning instrument.

'Plant-MFC produces enough energy to power sensoring systems for wetland monitoring.'

A picture of an experimental set-up to determine the oxygen transport by plant roots.

Oxygen from plant-roots

The Plant-MFC uses organic matter from the plants root system and soil that it is planted in to produce power. When oxygen is present close to the Plant-MFC, the power production is evidently negatively affected. Many waterlogged plants can transport (large) amount of oxygen to their root system, which can then come close or enter the Plant-MFC system. In my research I investigated the effect of this oxygen in the soil on the performance of the Plant-MFC so we can take this into account when these systems will be installed

Methane reduction

Many waterlogged systems such as wetlands are also producing methane. This methane is produced in a diffuse form, so we cannot capture and use it. This diffuse methane production is an enhanced greenhouse gas contribution that we would like to prevent. The microorganisms in the Plant-MFC compete for the same food as the microorganisms that are responsible for the methane production. In my research I looked at the effect of implementing a Plant-MFC system in methane producing wetlands. The first (lab) results indicate that there is indeed a reduction, in some cases even consumption, of methane that would otherwise be produced in the wetland.

'Build a new pilot system in relevant and dedicated wetland systems.'

Future application of the Plant Microbial Fuell cell

The outcomes of my research can contribute to the implementation of large-scale sensoring systems in natural wetlands that are responsible for buffering and naturally cleaning water systems all over the world as well as for constructed wetlands systems, specifically designed for certain wastewater streams. Many natural wetland areas are under pressure, leading to water scarcity and polluted water streams. Being able to effectively monitor them year-round can help preventing the deterioration of these before it will become irreversible. Constructed wetland systems have to comply with effluent norms to enable water reuse or safe discharge into the environment. A monitoring system can be of significant help achieving these quality norms and thereby contribute to safe water sources.

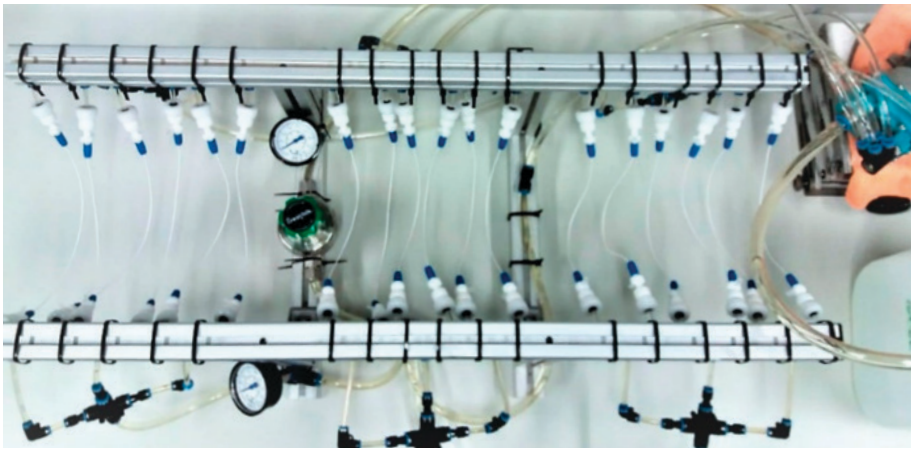
Many of our findings have been investigated in the lab or on relatively small scale outdoor. We recommend combining the findings that we have mentioned and use them to test the sensor in full-scale constructed as well as natural wetland systems. This way the potential benefits can be shown.

Nanofiltration membranes for the removal of salts and micropollutants

Daniëlle Scheepers, Eindhoven University of Technology

Layer-by-layer nanofiltration membranes

I studied the production and application of nanofiltration membranes with the layer-by-layer technique for the treatment of saline industrial water streams. Nanofiltration membranes have been used extensively to purify wastewater streams to produce reusable water in the process industry, for irrigation purposes, or as a drinking water resource. The layer-by-layer technique uses a porous membrane support that is coated by a series of alternating layers of oppositely charged polyelectrolytes (PEs).



A picture of assembling layer-by-layer membranes.

In my research, I studied the influence of several parameters during the fabrication of the layer-by-layer membranes on the membrane structure and performance. I specifically focused on the following parameters:

- Which polyelectrolytes can be used for the formation?
- How does the addition of salt to your polyelectrolyte solution affect the membrane formation?
- Which membrane composition results in the best removal of salts and micropollutants?

'Layer-by-layer nanofiltration membranes can be produced in a simple and ecologically friendly way.'

An example: $MgSO_4$ removal for layer-by-layer membranes with PDADMAC/PSS

$MgSO_4$ is a salt with relatively large hydraulic radii and bivalent ions, which in general makes it relatively easy to remove, compared to NaCl for instance. In general, the number of polyelectrolyte layers that are adsorbed on the nanofiltration membrane, increases the membrane resistance resulting in higher retentions of $MgSO_4$. I found out that there is a limiting retention possible after a certain number of adsorbed layers, because the size exclusion characteristics of the nanofiltration membranes are not improved.

'There is a certain amount of polyelectrolyte layers necessary to increase $MgSO_4$ retention after which the retention becomes constant.'

Remarkable results: The charge density of polyelectrolytes

With the types of experiments mentioned in the previous section, I learned more about the different parameters that have an influence on the formation of layer-by-layer membranes. By using two different polycations, which have a different amount of charged sites, the adsorption can be tailored.

The influence of the charge density and the ionic strength during layer formation has been researched in terms of polyelectrolyte adsorbance, membrane surface charge, and filtration performance. A low charge density is a limiting parameter for polyelectrolyte adsorption and retention, due to limited uptake of two bilayers. Consequently, it is impossible to form NF membranes with solely low charge density polyelectrolytes. For high charge density polyelectrolytes, increasing the ionic strength is crucial to increase PE adsorption. However, there is an opposite effect of ionic strength and charge density on membrane surface charge and pure water permeability. These opposite trends show the importance of simultaneously taking into account the charge density and ionic strength

'Charge density of polyelectrolytes is a crucial parameter for the formation of membranes.'

Asymmetric membranes

The knowledge gained on the charge density parameter resulted in a whole new field of research: asymmetric membrane formation. Here different polyelectrolyte chemistries are combined in one membrane. With this, the membrane performance can be tailored to the advantages of these polyelectrolytes. This resulted in the combination of low and high charge density polyelectrolytes, resulting in membranes with higher retentions for negatively charged ions.

A picture of the set-up to test the performance of the newly developed layer-by-layer membranes.

Unexpected outcomes

I also obtained some unanticipated results. For instance, if you change the application procedure of the polyelectrolyte layers from static dipcoating to dynamic flowing of the coating solutions results in very different performances. The latter coating strategy is preferred for upscaling the membranes into modules (see figure). However, this coating results in unwanted lower water permeabilities, while keeping the removal of components similar.

'Layer-by-layer membranes can be tailored for the treatment of different salts.'

Future use of layer-by-layer membranes for water treatment in fresh water-stressed regions

My research has shown that layer-by-layer membranes can be used for the treatment of specific salts and micropollutants. The toolbox of layer-by-layer membranes can be used to make highly negatively or positively charged membranes with specific pore sizes. However, the retention of small micropollutants, and monovalent ions is limited. This makes these membranes less suited for complete salt removal. I would recommend to further study the influence of the chemistry, functionality, and type of the polyelectrolyte on the layer-by-layer assembly. Small modifications can significantly influence the membrane, resulting in different advantages such as higher permeabilities, retentions, or selectivities. Additionally, long-term stability of these membranes in real operational conditions should be investigated.

'Different parameters can increase the application possibilities of layer-by-layer membranes.'

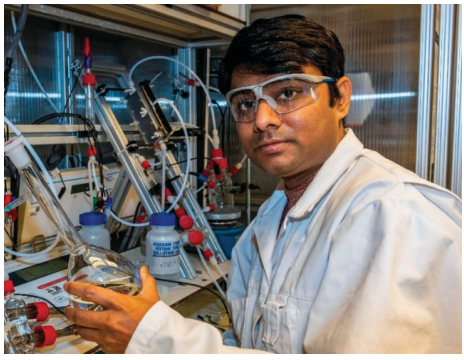
Advanced oxidation processes for the removal of organic compounds from cooling tower blowdown

Pradip Saha, Wageningen University & Research

Advances oxidation processes for cooling tower blowdown treatment

Industries are one of the biggest consumers of freshwater and producers of wastewater. A large part of the fresh water consumption of industries is used in cooling towers for cooling different process streams. After the cooling process, cooling tower water is discharged as cooling tower blowdown. Reuse of the CTBD can reduce the industrial freshwater footprint and enable them to become an eco-efficient and sustainable industry. Cooling tower blowdown contains a complex mixture of salts and organic compounds. Advanced oxidation processes (AOPs) to remove the organic compounds under saline conditions were studied. The principle of AOPs is to generate highly reactive radicals which are capable of degrading the organic compounds. In this research, four different AOPs, namely- electrooxidation, photocatalytic degradation, heat-activated persulfate oxidation and the UVC/vacuum UV process, have been evaluated and compared based on the following perspective:

- Which AOPs have the highest removal efficiency for organic compounds?
- Which AOPs have the lowest toxic by-products formation potential?



'Active radicles produced during the advanced oxidation processes can completely degrade organic compounds to CO_2 and water.'

Persulfate-based oxidation results in the highest organic carbon removal

The studied cooling tower blowdown contained 40-55 mg/L of total organic carbon (TOC), representing organic compounds. In addition, 450 mg/L chloride ions were present in the cooling tower blowdown. This ion influenced the advanced oxidation

processes. The influence of different advanced oxidation treatments on cooling tower blowdown composition is summarized in the table below:

Oxidation process	Total organic carbon TOC removal (%)	Chlorinated inorganic compound (ClO_x^-) formation	Chlorinated organic compound (AOX) formation
Electrooxidation	57	High	High
Persulfate based oxidation	95	~0	ND
photocatalytic degradation	50	ND	ND
UVC/vacuum UV process	54	ND	ND
ND= not detected			

The summary in the table above shows that persulfate-based oxidation can completely remove the organic compounds, whereas other oxidation processes could reach around 55%. At the same time, except electrochemical oxidation, all other processes generated a negligible amount of chlorinated compounds. Direct oxidation of the chloride ions on the electrode surface yields reactive chlorine species responsible for forming the chlorinated compound during the electrochemical oxidation process. Therefore, persulfate-based oxidation, photocatalytic degradation, and UVC/vacuum UV are suitable technologies for removing organic compounds without producing toxic by-products from saline wastewaters, such as cooling tower blowdown. From an application point of view, persulfate-based oxidation will be very interesting for two reasons:

- Sulfate-containing waste streams could be the source of persulfate.
- Waste heat from the cooling tower could be the source of heat to activate the persulfate.

Thus (re) use of waste sulfate and heat could make this process more sustainable by reducing additional energy and chemical consumption.

'Free chlorine formation should be avoided to minimize the toxic chlorinated by-product formation.'

The application of advanced oxidation processes for other saline water streams

Not only cooling towers, but also many other industrial wastewaters contain organic compounds and chloride ions. Moreover, drinking water production companies are becoming more concerned about removing organic micropollutants in moderate saline conditions. Advanced oxidation processes have a high potential to remove organic compounds from wastewater; however, they face challenges due to toxic chlorinated by-products formation during organic compound removal. This research shows that the influence of chloride ions varied a lot in different processes. Also, the chlorinated by-product formation mechanism depends on the reactive chlorine species formation and distribution. For instance, free chlorine/ hypochlorite ions are the precursor of both organic and inorganic chlorinated compound formation. This precursor is dominant in the electrochemical oxidation process. This research provides an in-depth fundamental understanding of chloride chemistry in advanced oxidation processes, which could guide stakeholders to select a suitable technique to remove organic compounds in saline conditions without toxic by-products formation.

Scaling up

Lab-scale experiments show that persulfate-based oxidation, photocatalytic degradation, and UVC/vacuum UV could be applied in saline conditions. In the future

- The technical, economic, and environmental feasibility of these processes need to be studied.
- The selected process should be tested on pilot and full-scale, combined with other technologies when deemed necessary.

'Organic and inorganic by-products should be analyzed in all advanced oxidation studies.'

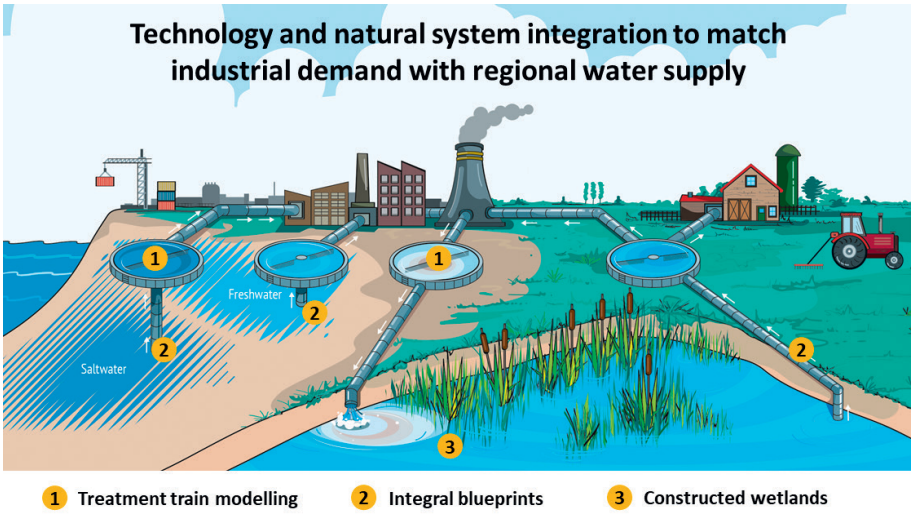

3

Research line 3
Technology and natural system integration enabling multi-sourcing and fresh water footprint reduction

Dr. Koen Wetser, Wageningen University & Research

In Water Nexus, saline water is considered as a useful resource, alleviating pressure on freshwater resources. Research line 3 aimed at developing integral solutions at system level and consisted of two work packages:

- In work package 1, models are developed connecting sources of different qualities with applications with different requirements. Solutions found in Water Nexus research lines 1 (quality and quantity distribution of water resources) and 2 (treatment technologies and requirements) are combined with existing knowledge on water treatment in the overall modelling on system level. This work package is divided in two parts: treatment train modelling and integral blueprints.
- Work package 2 focusses on the treatment of saline industrial water in constructed wetlands. These constructed wetlands can not only be used for water purification, but also as large volume buffers to solve problems with temporal variation in supply and demand. Treated water from constructed wetlands can either be used in industry again, or can be made suitable for agricultural use.



Overview of Water Nexus research line 3: Technology and natural system integration to match industrial demand with regional water supply. Research on (1) treatment train modelling for the treatment of saline water and saline industrial wastewater, (2) integral blueprints for the use of alternative regional water resources such as fresh groundwater, brackish/saline groundwater, rainwater and wastewater and (3) constructed wetlands for the treatment of industrial wastewater and water storage.

Alternative water resources for industry: Designing environmentally compatible regional supply networks

Joeri Willet, Wageningen University & Research

Designing new water supply networks

I studied the design of new decentralized water supply networks that use alternative regional water resources. Alternative water resources can be (brackish) groundwater, harvested rainwater from urban areas, or wastewater treatment plant effluent. When designing these new water supply networks there are several spatial and temporal challenges that must be overcome:

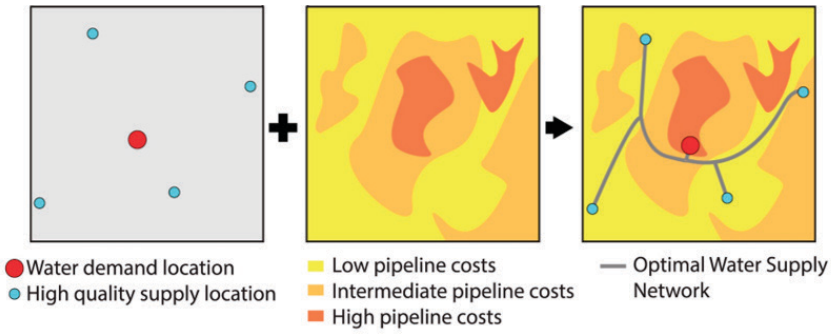
- Where is the water available?
- Where is the water needed?
- What is the quality of the water?
- When is the water available?
- What landscape characteristics affect the costs to transport water?
- Do we need water storage facilities?

In my research I developed WaterROUTE, which is a modelling tool to design new decentralized water supply networks that overcome these challenges while minimizing the economic costs.

An example: The spatial challenge of transporting water

There is enough freshwater available globally to cover all the current needs of humanity. Unfortunately these freshwater resources are distributed unevenly, which means that in some places there is water scarcity and in some places a surplus. Such a spatial mismatch in demand and supply can be solved by transporting water, generally through pipelines. However, pipelines are expensive! This means that before a new alternative water resource can be used the costs to place pipeline infrastructure must be considered in detail. These costs depend on the local characteristics of a region. For example: it is more expensive to place a new pipeline that passes through an urban area than through an agricultural area. By using geographic information systems tools (GIS) these local characteristics can be combined to make a regional overview of the costs to place pipeline infrastructure. This overview can then be used to design the optimal configuration of a new water supply network (see figure).

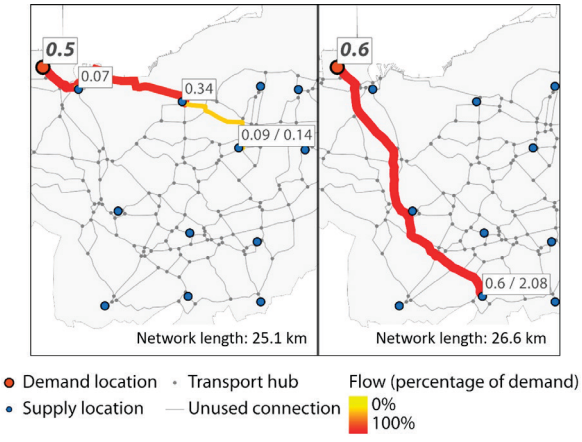
Small changes at the demand site greatly affect the configuration of a water supply network. Due to the limited availability of water at each of the supply locations the water supply network with the lowest costs can change drastically based on the demand at the demand site.



Determining the configuration of a new decentralized water supply network based on the local costs to place pipeline infrastructure.

Increasing the demand from 0.5 Mm³ year-1 to 0.6 Mm³ year-1 results in a completely different water supply network

I investigated the possibility to supply a large industrial water user with decentralized groundwater resources in the area of Zeeuws-Vlaanderen in the south of the Netherlands. The results show that depending on the demand of the industrial facility the configuration of the water supply network can be very different (see figure below). This knowledge is valuable for regional planners and water managers to design robust water supply networks.



Optimal water supply network for a demand of 0.5 and 0.6 Mm³ year-1. The labels represent the amount of water coming from each supply location and the total water availability in Mm3 year-1 (water/water availability).

Enabling the use of renewable alternative water resources for water stressed regions

My research can be used to make water stressed regions self-sufficient by enabling the use of renewable alternative water resources. WaterROUTE allows local stakeholders and decisionmakers to investigate water supply networks for different scenarios. Such scenarios can involve the reduction in regional water availability due to climate change, or the possibility to supplement freshwater with brackish water based on a fit-for-purpose water supply system. I would recommend to investigate water treatment in combination with decentralized water supply networks. By including water treatment in WaterROUTE it is possible to determine if water should be transported from far away, or if it is better to treat water that is close by. By combining WaterROUTE with water treatment models it is possible to create regional water supply networks that deliver water with the exact quality required by the user while minimizing costs.

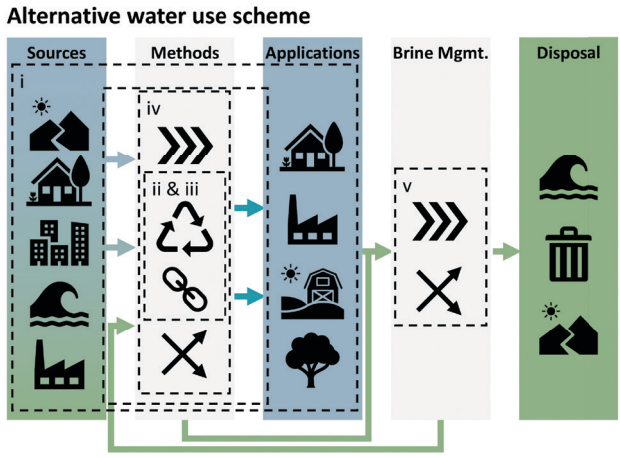
Alternative water use: From source to application

Jess Wreyford, Wageningen University & Research

Exploring alternative water sources, relevant end uses, and the methods for connecting them

Existing water use schemes have been shown to be unsustainable. To address water scarcity, I propose investigating the opportunities and constraints of using alternative water sources for various applications, thereby offsetting freshwater demand. Alternative sources include wastewater, brackish water, and other poor-quality water sources that are typically excluded from existing research. The objective of this research is to evaluate the complexities of alternative water sourcing and identify which methods are needed to improve its implementation. The research into alternative water use included:

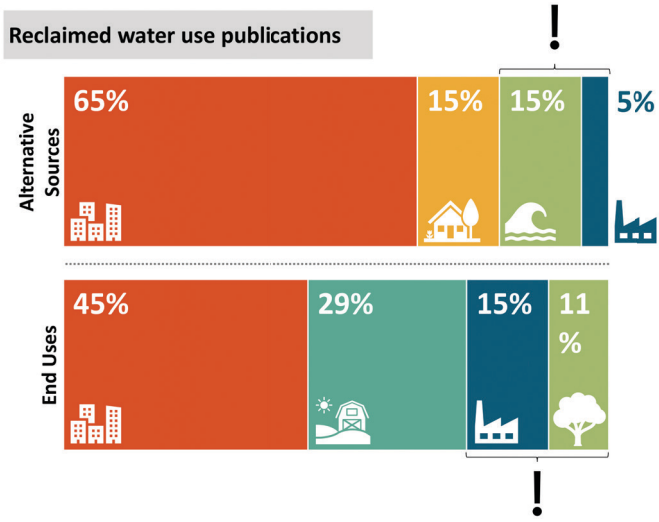
i reviewing the state of alternative water reuse;
ii developing a systems-level treatment technology model;
iii exploring the capabilities of treatment trains to connect sources and applications;
iv assessing and comparing feasible configurations using decision science; and
v reframing alternative water use from the perspective of brine management.



Schematic overview of the research performed by Jess.

The state of alternative and reclaimed water literature

- Majority of literature focuses on municipal sources and domestic end uses.
- Available source data does not often address end user concerns.
- Environmental and industrial end uses overlooked but have a great potential.
- Freshwater demand can be offset by using alternative sources for overlooked end uses.



An overview of the existing literature on alternative and reclaimed water use.

Systems-level modelling of treatment technologies:

- Theoretical and semi-empirical models were the most comprehensive analyses methods.
- Operating conditions play an important role on the severity of systems level impacts.
- For continuous mode electrodialysis, boundary layer and water transport phenomena are important to include for accuracy.

Treatment train performance for desalination

- Treatment train modelling requires accurate and technology specific evaluations.
- The order of technologies plays a significant role in the treatment train performance.
- Using a discrete-based approach results in a large number of results.
- Decision support is needed and must include environmental and sustainability indicators.

Decision science for assessing alternative water options

- The DEA method makes it possible to evaluate integrated water supply alternatives.
- The output of the DEA method is a refined list of options which can support decision-makers.
- Treatment and transport were found to be complimentary measures for supplying water.
- Users should consider this framework as a tool for decision-support, not decision-making.

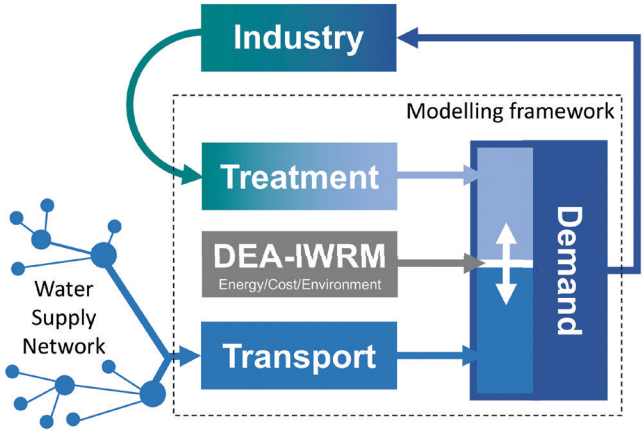
Reframing brine management

- Brine management is often an afterthought that can cause major constraints to the success of alternative water use.
- Focusing on brine quality requirements can open up options for cross-sectoral water reuse with reduced economic and environmental impacts.

The future application of newly developed tools to enhance alternative water use in water stressed regions

The identification of standards in the research can be used to create a base knowledge of what water qualities can be used. In addition, the developed treatment train model can be used to identify the possibilities for water reuse through treatment and make it possible to see what water reuse options are feasible. Furthermore, the decision support tools can be used to evaluate options for alternative water use that includes the perspective of economic and environmental impacts. For further future application, knowledge about the following subjects should be extended:

- Establishing standards and quality targets for water reuse applications.
- Alignment of standards and source data to connect and promote alternative water use applications.
- Expanding treatment train modelling to include additional and more novel technologies.
- Focus on brine management and the alternatives to disposal.
- Centering brine requirements in the evaluation methods of water treatment.



A modelling framework for industrial water supply.

Treatment of saline industrial wastewater in constructed wetlands

Dr. Thomas Wagner, University of Amsterdam / Wageningen University & Research

Pilot-scale constructed wetlands for the treatment of cooling tower water.

Natural waste water treatment systems: constructed wetlands

I studied the application of constructed wetlands for the treatment of saline industrial water streams. Constructed wetlands are essentially basins filled with sand and gravel that are planted with plants, such as common reed. In these constructed wetlands, different natural mechanisms work simultaneously to clean water from its contaminants: degradation by microorganisms, adsorption, degradation by sunlight, plant uptake, filtration etc. In addition, constructed wetlands provide ecological and aesthetic value by providing habitat for various animals. In my research, I studied which constructed wetlands designs are optimal for the removal of chemicals from different saline industrial water streams: cooling tower water and produced water from the oil industry. I especially focused on the removal mechanisms:

'Constructed wetlands can treat water and provide ecological and aesthetical value at the same time.'

- By which mechanisms are different chemicals removed?
- How are these removal mechanisms influenced by parameters, such as the temperature and the salinity?
- How can I adapt the design of the constructed wetland in such a way to have the highest removal efficiency possible?

An example: Benzotriazole removal in a constructed wetland

Benzotriazole is a commonly used chemical in many industries to prevent corrosion of the pipes. With laboratory-experiments, I found out that constructed wetland microorganisms can degrade benzotriazole, but mainly in the presence of oxygen. Therefore, a constructed wetland that is supposed to remove benzotriazole from

cooling tower water should provide oxygen-rich conditions to the microorganisms. This oxygen-rich conditions can be created using specific ways of designing a constructed wetland. I tested this in actual differently designed constructed wetlands outdoors, and indeed, the oxygen-rich constructed wetlands were better able to remove benzotriazole than the constructed wetlands in which less oxygen was present.

'Constructed wetlands can remove industrial chemicals from cooling tower water.'

The constructed wetland removes different types of chemicals from industrial wastewater

With the types of experiments mentioned in the previous section, I learned more about different constructed wetland removal mechanisms as well as the application of constructed wetland under real climatic conditions. Constructed wetlands were well able to remove different industrial chemicals from saline water, such as biocides and corrosion inhibitors. By using a new technique for the analysis of unknown chemicals in water – non-target screening – I found out that biocides are very reactive: for the first time it was shown that they interact with each other and constructed wetland material and form new chemicals, that are actually less toxic than the individual biocide itself. This allowed their removal in the constructed wetland.

'Constructed wetlands are suitable for treatment of saline water but need relatively large land surface area and moderate temperatures.'

From control laboratory conditions to less controlled outdoors conditions

The use of the outdoor constructed wetlands confirmed many ideas that we had as a result of performing laboratory-experiments:

- Ideas about the effect of temperature: lower temperatures result in a lower microbial activity and therefore a lower removal efficiency of the constructed wetland; High temperatures result in a higher evapotranspiration and therefore an increase in the salinity.
- Ideas about the different constructed wetland designs that can be used for the removal of different chemicals.

We also obtained some unanticipated results. For instance, if you combine two different constructed wetland types in a constructed wetland train, and the first constructed wetland in the train does a very good job in removing nutrients, the plants

Differences in plant survival in the pilot-scale constructed wetlands treating cooling tower water.

in the following constructed wetland will suffer from a nutrient deficiency and eventually die off earlier in the autumn season (see figure).

A combination of constructed wetlands and desalination technologies is needed for complete treatment and desalination of saline wastewater

My research has shown that constructed wetlands can be used for the treatment of various saline water streams worldwide. Especially cooling tower water is well suitable for the treatment by constructed wetlands: the salinity generally is not that high to have a negative effect on the microorganism and plants in the constructed wetland, and the constructed wetland is well able to remove various chemicals from the cooling tower water that hinder its further reuse. The constructed wetland does not remove the salts from saline water streams, and high temperatures in summer even result in an increased salinity of the water as a result of evapotranspiration. Therefore, desalination of a saline stream treated by the constructed wetland is still needed if fresh water is required. The constructed wetlands do suffer from a few disadvantages that might hinder their successful application:

- Low temperature in the winter has a negative effect on the treatment efficiency of the constructed wetland, and therefore additional treatment might be needed if certain water quality requirements need to be met.
- The constructed wetland needs quite some land surface to treat a large-volume water stream, and land surface in industrialized or densely populated areas is often scarce.

'Technological measures to enhance the efficiency of removal mechanisms without losing the green identity.'

Future technological improvements of the constructed wetland

I would recommend to further study small technological improvements to the constructed wetland that can improve its removal efficiency and overcome the disadvantages mentioned in the previous section, but that do not reduce the constructed wetland's green identity. An example of this could be the use of a substrate material with a higher adsorption capacity than sand. Another option might be to stimulate the activity of the microorganisms in the constructed wetlands, for instance by pumping in air or providing excess heat from the cooling tower in colder periods.

PhD-students working on integrated solutions for regional fresh water management at the Witteveen+Bos office, Amsterdam.

Integration of the technologies developed in research lines 2 and 3. In this picture a series of constructed wetlands containing a Plant-MFC, which is combined with nanofiltration and electrochemical oxidation for the treatment of cooling tower water of Dow Terneuzen at the premises of Evides.

4
Synthesis of outcomes Water Nexus research

Outcomes of the scientific research in the various research lines and their direct impact on the core business of end-users

The scientific research in Water Nexus resulted in the development of a toolbox of novel and state-of-the-art output with a focus on industrial water provision and water reuse containing new digital tools for regional water management, water treatment technologies and innovative concepts for future management of fresh and saline water in coastal areas. Many of these tools from this toolbox could directly be taken up by the consortium end-users in their daily operations. A detailed description of this output can be found in the open access scientific papers that were published during the duration of Water Nexus, and papers that are still to be published. An overview of these publications is provided in the next chapter. Below, an overview of the output of Water Nexus is provided:

Digital tools for regional management of saline and fresh water

1.1.1. Rapid regional mapping of salt-fresh water distributions

A methodology to combine airborne electromagnetic mapping (AEM) with geological information of (economically) optimal 3D-mapping of regional groundwater salinity distribution has been developed. In addition, AEM inversion was integrated with forward density-dependent groundwater salinity modelling for a joint estimation of salinity distributions and hydrogeological parameter estimations. The methods have been coded in an integrated set of scripts that together make up an open source workflow that can be used in efficient and accurate salinity mapping by other parties.

TNO innovation for life

100 JAAR GEOLOGIE IN KAART

TNO

'The use of Airborne Electromagnetic Measurements (AEM) to determine change of the salinity distribution in the groundwater may also lead to improvement of the lithological characterization of the subsurface in our model GeoTOP.'

Deltares

Fundamental knowledge on the efficiency of Airborne ElectricoMagnetic surveys that have mapped the fresh-brackish-saline groundwater distribution in the coastal zones on Zeeland and Vlaanderen (via the projects with the acronym FRESHEM) were valuable for Deltares: which inverse techniques are best in reducing the errors; what is the optimal flightline spacing given a certain amount of geological information; what information is needed to assess whether an additional AEM survey can detect changes in groundwater salinity due to e.g. groundwater extractions. The above-mentioned information will for instance be used in the planned survey FRESHEM for most lower parts of the Netherlands.

1.1.2. Rapid modelling and scenarios for strategic policy development

Datasets of hydrogeological profiles and onshore and offshore salinity distributions of the global coast were obtained. In addition, for the first time the exploitable offshore freshwater volumes were estimated. Furthermore, the effects of climate change and sea-level rise on onshore freshwater resources were predicted. Also a Q-GIS application was built that can be used to interrogate the data and build simple groundwater flow and salinity models of selected coastal stretches. The models and datasets of this research are publicly available for use by other parties.

Deltares

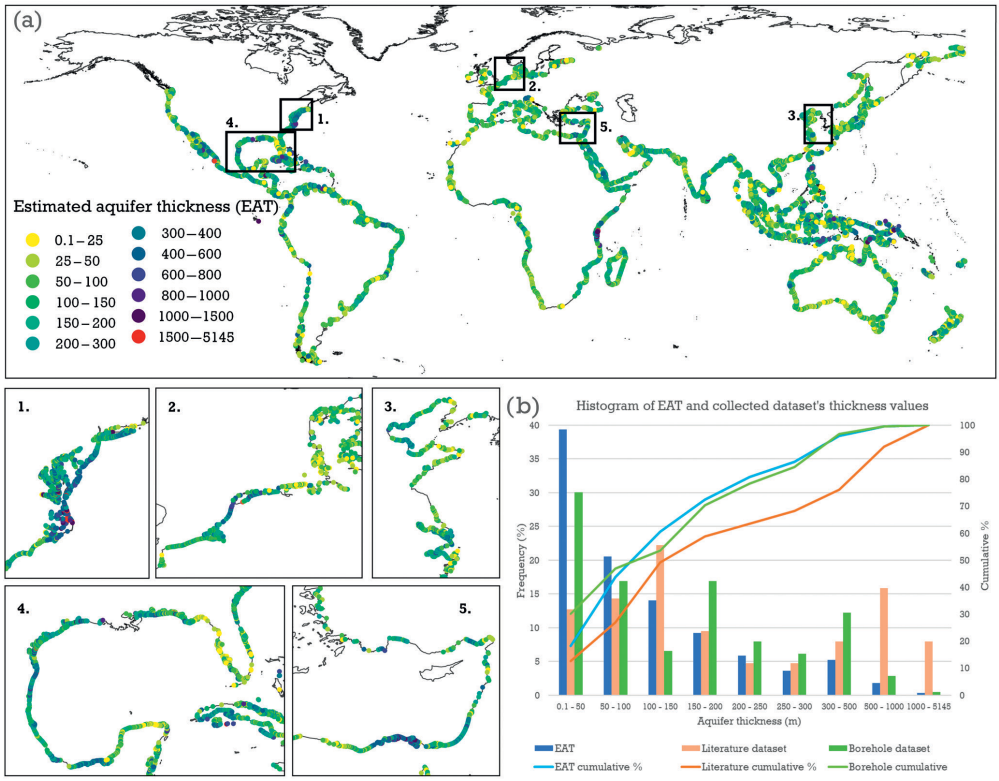
'The analysis under what conditions offshore fresh groundwater resources exist, including a spatial distribution of fresh groundwater in the coastal zones around the world were adopted in various other projects; what is the impact of different sea-level rise scenarios on coastal fresh groundwater resources. These results are for instance used for the Future Water Challenges Project of PBL.'

1.1.3. Operational management of regional salt-fresh water resources

A model-predictive control framework for optimal control of surface water levels and salinity levels in channel networks, such as polders, was developed. Furthermore, methods to select the optimal location of salinity observation in model-predicted control frameworks were selected. A C++ software package was built that can be used to setup any model-predictive control system for any hydrological variable depending on observations and models available.

Deltares

'Research line 1.1.3 resulted in a better understanding of optimizing the management of fresh surface water in low-lying polder areas; what tools are needed to better assess such an optimizing management system. These results are for instance used, e.g. for projects we execute for programmes like the Knowledge Programme Zeespiegelstijging (client Rijkswaterstaat) and the Delta Programma Zoetwater.'



Global map of estimated aquifer thickness at the coastline and zoomed areas (Zamrsky et al., 2018), research line 1.1.2.

1.2.1. iDrain – Anticipating drainage systems in salt affected lowlands.

An open-source model tool has been delivered that allows the user to determine how water inputs (rain, irrigation) impact groundwater levels for fixed and for adaptable drainage. It is demonstrated how the groundwater level can be stabilized much better under adaptable drainage operation. For the case that actual rainfall is only a prognosis, as is irrigation aimed at preventing water shortages, the tool is shown to

stabilize groundwater levels effectively. Uncertainty bounds are quantified. For the presence of saline groundwater underlying fresh water lenses, lens as well as mixing layer thickness are quantified.

3.1.1. Integral Blueprints

A modelling approach for the design of water supply networks using alternative regional water resources is developed. The model, WaterROUTE (Water Route Optimization Utility & Evaluation tool), can generate optimized water supply networks for the supply of alternative water sources, such as regional fresh, brackish and saline groundwater, rainwater and wastewater to an industrial demand location. WaterROUTE incorporates the amount of water required at the demand location, the maximum allowed salinity of the water and the effects of land use on pipeline infrastructure costs. Methods from geographic information science and mathematical programming are connected with hydrological models. WaterROUTE was tested on an industrial case study of DOW Terneuzen in the region of Zeeuws-Vlaanderen in the south of the Netherlands. The model makes it possible to create decentralized water supply networks which provide fit-for-use water based on the requirements of the user. It is a valuable tool to evaluate multiple water supply scenarios for long term regional planning and decision making.

Dow Benelux B.V.

'The ability to use regional models to optimize infrastructure needs supports the development of a cost effective and sustainable water management system on the broader watershed level'.

The impact of saline water on nature and nature-based water treatment systems

1.2.2. iNurture: Balancing nature between brackish and fresh.

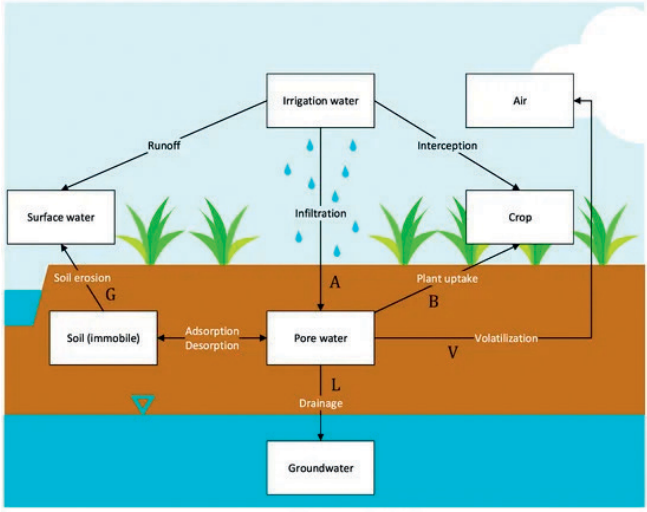
While salinity effects have been investigated in the context of agriculture for a long time, this was much less the case for nature areas. In this project, the impact of salinity was studied for groundwater-dependent terrestrial ecosystems. At relatively mild salinities (compared to those investigated for agriculture), an impact can be expected, for instance affecting which species can be found in an area. As salinity, e.g. due to up-concentrating of salts in case of significant evapotranspiration, may be enhanced compared with surface water that feeds the subsurface, this process needs to be taken into account.

KWR Water Research Institute

'Salinity stress is an increasing problem for agriculture and natural ecosystems. The insights from Water Nexus contribute to the knowledge base on this topic, which we could incorporate in our applied research programs like COASTAR and implement in tools like Waterwijzer Natuur.'

1.2.3. iRe-use – Economizing marginal (waste) water

Swell-shrink induced structure deterioration of sodic-saline soils has been given a theoretical foundation from the 1970-ies onward, but this remained limited to nano-scopic insights. This project upscaled such insights to soil aggregates and provided results that compare very well with field scale observations. To also enable an a priory assessment of whether irrigation with poor quality water will be sustainable or not, a framework has been developed that addresses soil, crop and groundwater quality in an integrated way. This framework has been illustrated for 'conventional' as well as emerging contaminants.



Schematic representation of the environmental compartments in the framework for assessing the impact of irrigation with saline water (Cornelissen et al., 2021), research line 1.2.3.

KWR Water Research Institute

The research in research line 1.2.3 provides insight in the possibilities on using brackish water as alternative water resource for e.g. industrial applications. The use of alternative water resources and thus a decreased groundwater exploitation will be an important topic of research for the coming years.

2.3.2. The application of the plant microbial fuel cell in saline environments

A screening was performed to find suitable plants for usage in plant microbial fuel cells supplied with saline cooling tower blowdown water. Spartina anglica and Limonium vulgare were found to survive in seawater with increasing salt concentration while Phragmites australis died after 60 days. However, Phragmites australis was found to grow in cooling tower blowdown and to produce power. The maximum power density was 1.08mW/m2 PGA. In a following experiment, oxygen diffusion from the plant roots

in a plant microbial fuel cell was successfully visualized. The roots system of a living plant excreted oxygen into the anode and this was shown to reduce the amount of current produced, due to changes in the redox conditions. Dead plants did not excrete oxygen into the anode. The current in these cells was higher than in those of the living plants. A literature study provided an overview of the Plant-MFC and its innovative environmental technological applications. Since the development of the first Plant-MFCs in 2008, research led to further understanding of the working principles and various new applications. The Plant-MFC is suited to power sensors or act as sensor by itself. The technology is integrated in various systems including green electricity roofs, constructed wetlands, rice paddy fields, tables and road-lightning applications. The electricity is used for numerous demonstrations to power cell phones or radio's. Electricity generation is combined with a unique combination of microbial, geochemical, electrochemical and plant processes that allows new applications. Services provided include methane emission reduction, water treatment, plant growth, food production, nature preservation, agriculture monitoring, green electricity experience, education, nutrient recovery, social awareness, pollutant removal and beyond. Valorization of these services is done by companies and designers in collaboration with several researchers and other stakeholders.

Plant-e

'Fundamental insights in some of the working principles of the Plant-MFC and its interactions with the soil and plants broadened our understanding of the ongoing processes. Due to a better understanding of the processes going on, we can change the design of our products and tailor them to the local circumstances. Moreover, some of the new insights have broadened the business model: we apply Plant-MFCs in market segments now where we did not do so before.'

3.1.3. Treatment of saline industrial wastewater in constructed wetlands

Constructed wetlands are man-made wetland systems in which different mechanisms are responsible for the removal of contaminants from water. Lab experiments were performed to simulate these mechanisms and determine the biodegradation, photodegradation, and adsorption efficiency for a set of target chemicals that are representative for industrial wastewater. In addition, pilot scale constructed wetlands were built with a focus on micropollutant removal from saline industrial wastewaters. A pilot-scale wetlands build for treatment of cooling tower water showed a high removal of TOC, PO4, and NO3 in the subsurface flow wetlands. Conditioning chemical benzotriazole was removed up to 100% in the subsurface flow wetlands. The electrical conductivity of the synthetic cooling tower water is not impacted by constructed wetland treatment, hence desalination is still needed. Laboratory-scale wetlands build for the treatment of produced water in hot arid conditions show that an increasing salinity impacts the removal of target chemical benzotriazole as a result of a negative influence

on the microbial activity. In addition, increasing salinities have a negative influence on the growth of common constructed wetland plants. The high temperatures result in an elevated electrical conductivity after treatment, which might hinder further reuse.

Shell Global Solutions B.V.

'The further exploration of constructed wetlands in an integrated line-up, building on our existing experiences with constructed wetlands in Nimr (Oman), yielded valuable insights for Shell.'

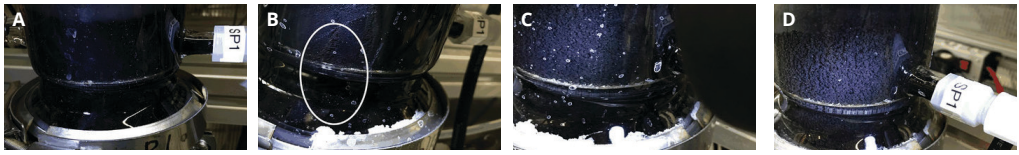
Evides Industriewater

'Water Nexus was a joint project with many partners. This research community created a wide network and input from different points of view. For our case the development of the wetland concept was a highlight.'

The impact of saline conditions on biological wastewater treatment

2.1.1 Anaerobic sludge granulation at highly saline conditions

Under anaerobic conditions it was relatively easy to form granules on saline wastewater (5 and 20 g sodium L-1). In addition, excellent treatment performance was achieved and the biomass exhibited a sufficiently high activity that will allow an economically attractive application in practice. This promising result could be attributed to the presence of a small quantity of a proteinaceous substrate in the (synthetic) wastewater. This substrate acts as a precursor for the microbiological production of so-called osmolytes, organic compounds that the microorganisms use to compensate for the osmotic pressure they experience from the salt in their environment. It was also demonstrated that the same proteinaceous substrate allowed the formation of well settling, strong and robust granules. The underlying mechanism is not entirely clear but most likely is related to the type of extracellular polymeric substances (EPS) the microorganism can form because these EPS ate key components for aggregation of microorganisms into granules. Finally, in a side study EPS were extracted from anaerobic granules and used to make a biopolymeric membrane. Electrodialysis experiments showed the EPS function as a cation-exchange membrane, i.e. selectively passed cations such as sodium and potassium but repelled anions such as chloride. Even more surprising is that these membranes exhibited selectively of sodium over potassium. Perhaps in the future this may have a practical application, for example in horticulture where potassium is an important nutrient but sodium is an undesired ion.



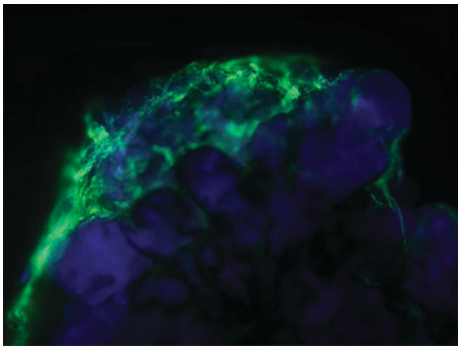
Granular sludge formation at 20 g Na^+/L at a) day 4; b) day 23; c) day 33; d) day 43 (Sudmalis et al., 2018), research line 2.1.1.

Nijhuis Industries

'Especially the research into varying salinities of the wastewater were of specific interest, as this is often a difference between research under controlled conditions and the application under real conditions. The results indicated that the anaerobic granular sludge adapted to high salinity could handle more variations then initially expected. This means that biological wastewater treatment can be applied in a broad range of industrial high saline wastewater.'

2.1.2. Treatment of high saline water with aerobic granular sludge

Under aerobic conditions it was possible to form stable and robust granules, even under very high salinity levels. This is very promising because it enables treatment of, for instance, sewage that is generated in delta regions where seawater is used for toilet flushing. The granules also remain stable, even after periods where the seawater was diluted by (non-saline) rainwater. Exposure to such rainwater events temporarily gave a deteriorated treatment performance but this rapidly recovered after the rainwater event. Interestingly, similar to anaerobic granules also in aerobic granules EPS plays an important role. Detailed identification of these EPS showed sialo acids were important functional groups in these EPS. It is known that these acids protect the galactose residues in EPS against enzymatic attacks and herewith probably contribute to the stability of aerobic granules under saline conditions. Also the production of osmolytes to counteract the osmotic pressure was observed with trehalose being the main osmolyte. In summary, both anaerobic and aerobic granular reactors were demonstrated to be promising treatment methods for saline wastewaters and this expands their application horizon from fresh to saline wastewaters.



Fluorescence in-situ hybridization analysis of an aerobic granule, highlighting the presence of different bacteria (de Graaff et al., 2020), research line 2.1.2

Royal HaskoningDHV

'Research with aerobic granular sludge showed that this can operate very stable and with a good performance when treating high saline wastewaters. For Royal HaskoningDHV this was a confirmation that our Nereda® technology is a satisfactory solution for the treatment of industrial wastewater.'

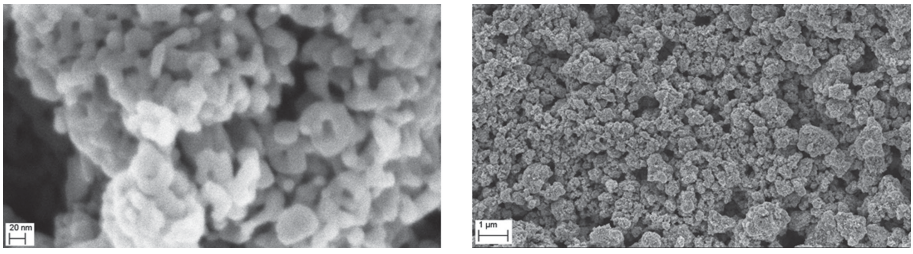
Paques

A main highlight of the research in research line 2.1 is the fact that both under anaerobic & aerobic conditions, we found that saline water is treatable, whereas before this research was executed, there had always been question marks related to this.

Technological improvements for the treatment of saline water streams

2.3.1. New electrode materials for the electrochemical oxidation of saline water

A series of studies was performed to develop and compare new electrode materials with a high removal efficiency, a high electrode stability and low toxic by-product formation. In a first study, substoichiometric TiOx(:Nb) electrodes were prepared by electrochemical self-doping via cathodization of rutile TiO_2 substrates with different counter electrodes. It was revealed that the use of inert counter electrodes, such as boron-doped diamond electrodes, is mandatory. Among all samples prepared, titania substrates treated with BDD counter electrodes led to the lowest layer resistance.



Scanning electron micrographs of TiO_2 films (Brüninghoff et al., 2019), research line 2.3.1

For Nb-doped and (undoped) TiOx, recovery of charge transfer properties after passivation by polarization switch in neutral media is a promising approach. In a second study, various electrode materials, namely Ti, platinized Ti, electrochemically reduced TiOx and Ir and/or Ru-mixed metal oxide electrodes were evaluated for their performance in reduction of low concentrations of hypochlorite and chlorate. None of the electrodes showed reduction of chlorate under the conditions studied. However, significant removal of hypochlorite was observed, with Ti electrodes being most effective. Rotating disk electrode experiments revealed that hypochlorite

reduction on Ti and Pt electrodes is mass transport limited. Based on this observation, porous Ti based hollow-fibre electrodes were used to mitigate the revealed mass transfer limitations. Using inert gas purging through the fibre, convective motion of the electrolyte close to the electrode surface was obtained leading to a significant improvement in the reduction rate of hypochlorite and a reduction of the toxicity of the solution.

2.3.3. Nanofiltration membranes for the removal of salts and micropollutants

Porous membranes were coated by alternating layers of oppositely charged polyelectrolyte solutions. Two sets of strong polyelectrolytes: poly(acrylamide-co-diallyl dimethylammonium chloride) (P(AM-co-DADMAC))/ poly(sodium 4-styrene sulfonate) (PSS) and polydiallyl dimethylammonium chloride (PDADMAC)/ PSS, with a polycation charge density of 32 and 100% respectively were studied in terms of membrane characteristics, charge, performance, and stability. A low charge density showed to be a limiting parameter in terms of polyelectrolyte nitrogen adsorption and retention, due to the limited uptake of two bilayers. This is an indication of restricted charge overcompensation during the layer-by-layer process. It is not possible to produce NF membranes with solely P(AM-co-DADMAC)/PSS layers. For high charge density polyelectrolytes, increasing the ionic strength is crucial to increase the polyelectrolyte adsorption and with that the $MgSO_4$ retention. An increasing ionic strength results in a permeability increase for P(AM-co-DADMAC) based membranes and a decrease for PDADMAC based membranes. Moreover, the surface charge increases with a decreasing ionic strength for P(AM-co-DADMAC) and vice versa for PDADMAC based membranes. These opposite trends undoubtedly show the importance of simultaneously taking into account the charge density and ionic strength to control the performance of layer-by-layer nanofiltration membranes for water treatment. In a following experiment, the retention of ions and micropollutants from cooling tower water and stability towards hypochlorite for the two coatings was tested. The main findings were that the membrane characteristics can be tuned and the retention can be improved with the addition of two bilayers of P(AM-co-DADMAC)/PSS. The best performance is found for (PDADMAC/PSS)7 + (P(AM-co-DADMAC)/PSS)2. The exposure to hypochlorite shifts PDADMAC/PSS membranes from cationic to anionic selective membrane. (PDADMAC/PSS)7+(P(AM-co-DADMAC)/PSS)2 is an anionic selective membrane with a high membrane chemical stability > 225000 ppm hours.

Witteveen+Bos

'The micropollutant removal technologies and constructed wetland ecoshape solutions were of major value to W+B as several consultancy and engineering projects related to circular water challenges were carried out or are under requests of proposal.'

2.3.4. Technology comparison and integration for the treatment of cooling tower water

Various laboratory experiments were performed to develop an integrated treatment train for the treatment of cooling tower water. In a first experiment, electrochemical oxidation of benzotriazole with different electrolytes was studied for boron-doped diamond electrodes. Electrochemical oxidation of benzotriazole was more efficient in the presence of sulfate ions than in the presence of chloride ions, while less chlorinated products were performed. In a second experiment, a boron-doped diamond and mixed-metal oxide electrode were compared in terms of cooling tower water treatment efficiency. The boron-doped diamond electrode demonstrated the highest removal efficiency for target compounds, but measures are required to limit the production of chlorinated by-products. A third experiment showed that the combination of electrochemical oxidation followed by a constructed wetland can result in an effluent with a less toxic final product due to the removal of chlorinated by-products in the constructed wetland. In a forth experiment, various advanced oxidation processes were compared in their removal efficiency for organic compounds from cooling tower water and chlorinated by-product formation. Heat-activated persulfate oxidation, photocatalytic degradation, and UV-C and vacuum-UV were capable of removing humic acids from cooling tower water, without producing chlorinated byproducts.

3.1.2. Alternative water use: From source to application

Two modelling frameworks were developed for the treatment and use of alternative water sources: (1) A hybrid-modelling framework (DESALT) for evaluating and comparing desalination treatment trains and (2) a modelling framework for the comparative analysis of integrated treatment and transport technologies. The DESALT framework generates treatment trains and then systematically evaluates them using physics-based evaluation methods. DESALT accounts for technology limitations, operating conditions, product water requirements and user preferences. The result is a list of eligible and preferred treatment trains with their corresponding operating conditions. The treatment versus transport modelling framework assesses alternative water supply configurations comparing on-site desalination (treatment) and off-site water sourcing (transport). The model identifies the preferable configuration based on economic and environmental indicators. Both frameworks were tested on an industrial case study.

Dow Benelux B.V.

'The development of a very broad spectrum of new and innovative water treatment technologies and models were among the firm highlights of the project.'

Integration of scientific research in Water Nexus towards regional concepts for sustainable fresh water use

Integration of the research in Water Nexus has led to both improved mechanistic insights in water treatment technology processes as well as improved insights in hydrological processes on a watershed-scale as a result of multidisciplinary scientific research. To integrate the knowledge obtained in the individual research lines in Water Nexus, the Zeeuws-Vlaanderen region in the Netherlands, where end-users Dow Benelux B.V. and Evides Industriewater are located, was used as basis for various case-studies.

Regional availability of fresh and saline water

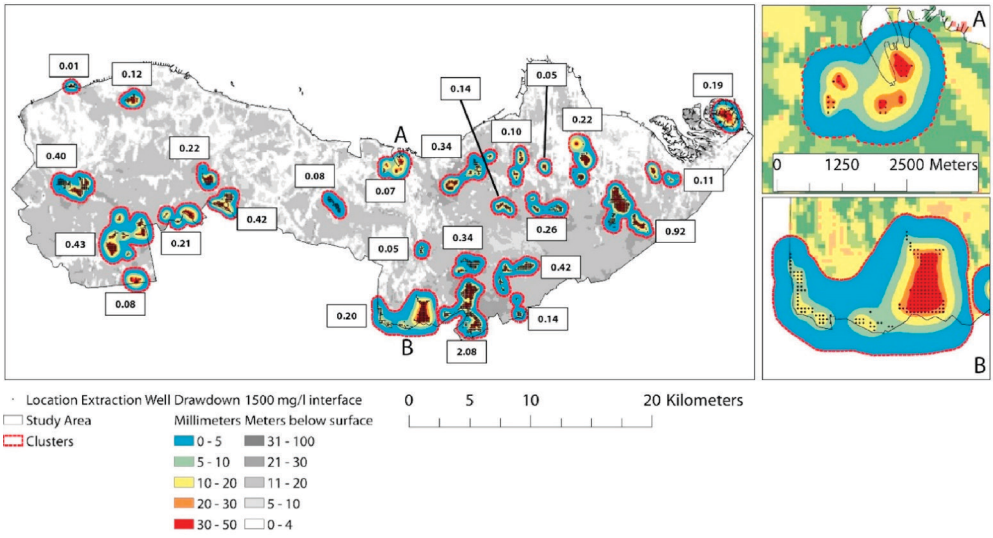
Researchers in research lines 1.1 and 3 have performed an in-dept analysis of the fresh and salt water distribution in the subsurface of the Zeeuws-Vlaanderen region. The Zeeuws-Vlaanderen region is characterized by limited water storage capacity due to its geomorphological and geohydrological constraints. Therefore, the region relies on the transport of water from various sources to provide the local industry and agriculture with sufficient fresh water during the whole year. Stakeholders in the Zeeuws-Vlaanderen region would like to become less dependent on external fresh water resources. One option to do so, is to use its own subsurface fresh water resources, but therefore it is critical to know where these are located, and how much can be extracted without adverse effects on ecosystems. Research line 1.3 has shown that ecosystems can be extremely vulnerable to salinization, resulting in soil deterioration and a shift of plant communities towards salt-tolerant plants. Several measures can be taken to avoid salinization of surface water and ecosystem damage, such as the use of adaptive drainage as studied in research line 1.2 and optimized polder flushing strategies, as developed in research line 1.1. In addition to ecosystem damage, extraction of local fresh water should not result in large changes in the subsurface distribution of salt and fresh water as a result of salt water intrusion.

The airborne electromagnetic mapping performed in research line 1.1 provided the volumes of fresh water that were present in the subsurface of the Zeeuws-Vlaanderen region. This could be used as input for a model developed in research line 3 that assessed the quantity of water that could sustainably be extracted under different future scenarios. In addition, a network-model based on the extraction yields was developed that predicted the optimal transport network configuration based on water transport requirement, land use and pipeline costs.

Shell Global Solutions B.V.

'Screening of freshwater resources for sustainable future use of fresh water was of specific interest to Shell.'

Supply locations and available water supply at optimized extraction rates (Willet et al., 2020)

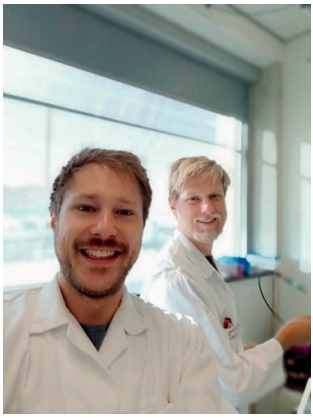


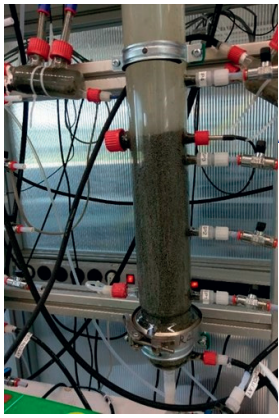
Treatment-trains for the treatment of saline water

Biological treatment for the treatment of saline municipal wastewater

The combined efforts of the researchers in research lines 2.1.1 and 2.1.2 have immensely broadened the fundamental knowledge on the adaptation of bacteria to saline conditions in both aerobic and anaerobic granular sludge treatment systems. Lab-scale reactors in both Wageningen and Delft have been operated under highly saline conditions, and stable operation has been achieved in both labs. A synthetic wastewater stream with salinity originating mainly from NaCl could successfully be treated in the anaerobic granular sludge reactor in Wageningen. Successful granulation was achieved, which was previously believed to be impossible due to displacement of divalent cations from the EPS matrix.

In Delft, a seawater-substituted aerobic granular sludge reactor has been operated up to complete removal of COD and phosphate. The granules appeared to be physically and biologically resistant to highly saline conditions, even after several salinity shocks. These two projects were integrated through a case study experiment. The effluent of the anaerobic process was connected to the influent of the aerobic process, by which initially high-strength saline wastewater should be cleaned down to low effluent concentrations. Through batch test experiments it could be concluded that phosphate levels decreased, and removal of acetate and propionate from the effluent was successful. This case study gives good basis for future integration of multiple process steps for the complete treatment of saline wastewater, such as those of the industries in the region of Zeeuws-Vlaanderen.





Selfie of 'Team Granular Sludge', working on their integrated experiment with both aerobic (left) and anaerobic (right) granular sludge.

Nijhuis Industries

'An open research question is still if nitrification was inhibiting for the aerobic granules at high salinity. Furthermore, a future research component could include a cooperation of two or more PhD students where they combine their technologies or make a comparison of their technologies for a case example. This will both enhance the exchange of knowledge and research experiences between PhD students, as well as look a further into the possibilities of the application of the research.'

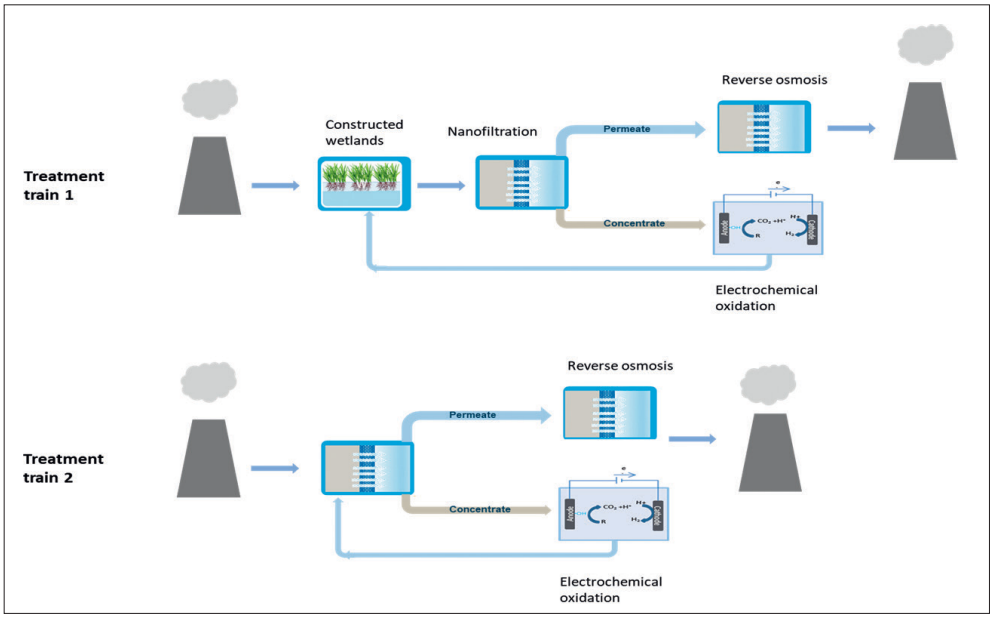
Paques

'Our main interest was to find out under what conditions saline water is treatable. For this we now have clearer boundary conditions. A very nice added value from the research was the finding that certain peptides can promote biomass agglomeration. We are going to study that further in our lab and in a follow up PhD project, to see if we can commercialize that.'

Combined physical/chemical and biological treatment for the treatment of cooling tower water

In a collaboration between researchers of research lines 2.3.1, 2.3.2, 2.3.3, 2.3.4 and 3.1.3, a pilot technology train was designed for the treatment of cooling tower water prior to its reuse in the cooling tower. The outcomes of the individual studies towards water technology optimization for the treatment of saline water streams were integrated in a treatment scheme for cooling tower water of end-user Dow Benelux B.V., in collaboration with Evides Industriewater and Plant-e.

The treatment-train consisted of a series of constructed wetlands, of which one contained a Plant-MFCs, followed by nanofiltration. The nanofiltration permeate was subsequently treated by reverse osmosis, while the nanofiltration concentrate was treated by electrochemical oxidation. Two versions of the treatment-train were studied, with and without the constructed wetlands, see also the figure below:



Two treatment scenarios for the treatment of cooling tower water from Dow Terneuzen.

The different treatment technologies within the treatment-train served various purposes:

Constructed wetlands	• Pre-treatment before membrane filtration, removal of fractions that can cause membrane fouling • Removal of small chemicals that are not retained by membrane filtration • Buffering of large water volumes
Plant-MFCs	• Monitoring the biological activity in constructed wetland
Nanofiltration *Electrochemical oxidation*	• Removal of divalent ions and large organic substances • Oxidation of organic substances from nanofiltration concentrate in a sulfate-rich solution
Reverse osmosis	• Removal of monovalent ions • Production of process water with a electrical conductivity of <1 mS/cm and <100 mg/L Cl^-

The complete evaluation of this treatment-train, also in terms of costs and energy-requirements, still needs to be finalized, but performing this integrated experiment has already provided valuable insights in the functioning of the different technologies:

- The series of constructed wetlands was able to remove fractions that could cause fouling of membranes of subsequent membrane desalination technologies, such as PO_4 and NO_3. In addition, various chemicals that are used to maintain proper cooling tower functioning were removed in the constructed wetlands. Due to the size of these chemicals, these chemicals were not removed by nanofiltration. An increase in the concentration of inorganic carbon in the constructed wetland effluent was observed.

Dow Benelux B.V.

'The applicability of green infrastructure to treat harsh process waters is of significant value to Dow in its ambition to use nature based solutions for technical issues.'

- Temperature fluctuations resulted in fluctuations in the electrical conductivity of the constructed wetland effluent. During high temperatures in summer, this could lead to significant increases in the salinity of the water.
- The Plant-MFCs in the constructed wetlands did not function properly during the complete runtime of the experiment. However, it was possible to deduct design rules for the future implementation of Plant-MFCs in constructed wetlands.

Plant-e

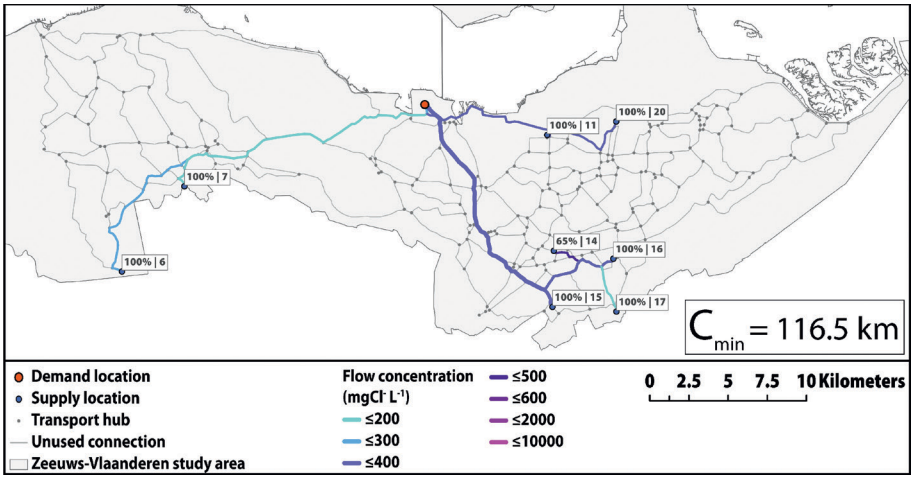
'P-MFCs in this constructed wetland did not work as a biosensor for chemicals in the cooling tower blowdown water because of too aerobic conditions caused by a low water level and possibly the flow of water as well, resulting in too high oxygen concentration in the anode. Results at moments when the flow was stopped or started (March and May 2020) and with high rain fall (September 2020) do show that a P-MFC can function in this constructed wetland if the right conditions are created.'

- Nanofiltration results in substantial removal of large organic compounds and divalent ions from the feed stream. Constructed wetland pre-treatment seemed to result in a pressure-increase of the membrane-system, possibly as a result of membrane-fouling due to the increased concentration of inorganic acids.

- Electrochemical oxidation of nanofiltration concentrate resulted in a higher removal of organics than direct electrochemical oxidation of cooling tower water that was performed in earlier studies, because increased organics concentrations in the nanofiltration concentrate overcame mass transfer limitations. Electrochemical oxidation of the treated cooling tower water did result in the formation of toxic chlorinated species, and thus requires attention for further processing of this stream
- Reverse osmosis was capable of reaching electrical conductivities below 0.1 mS/cm, while also reaching Cl^- concentrations of <50 mg/L with a recovery of >95%. Brine-production is a point of attention.

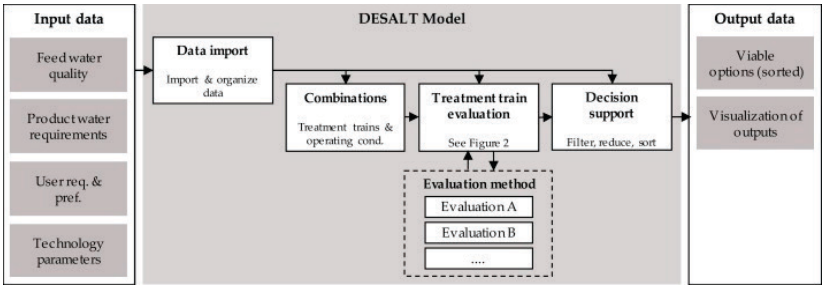
Connecting regional water demand and supply in quantity and quality

In the beginning of this chapter, it was explained that one option for the Zeeuws-Vlaanderen region to become more fresh water self-sufficient is to sustainably use its own subsurface fresh water resources. Another option is to reuse unconventional water resources that are not being used at the moment, such as brackish ground-water, treated municipal wastewater or saline industrial wastewater. This requires a focus not only on water quantity, but also on water quality. The regional water transport network-model developed in research line 3 was adapted to also take into account this quality aspect, such as the salinity in mg/L Cl^- in the figure below:



Optimal network configuration for the supply of the water with the lowest possible salinity to Dow Terneuzen in Zeeuws-Vlaanderen, research line 3 (Willet et al., 2021).

When the supply of suitable water resources is not sufficient, treatment technologies can be used to adapt the quality of the water to the meet the quality requirements. The DESALT model was developed in research line 3 as a tool for case-specific evaluation of desalination technology trains, consisting of desalination technologies, such as electrodialysis and reverse osmosis.



Schematic overview of the DESALT desalination technology evaluation and decision support tool (Wreyford et al., 2020).

RoyalHaskoningDHV

'A highlight of Water Nexus was that so much understanding was obtained concerning the value of saline water and that it still can have a valuable position in finding solutions for the challenge of water scarcity.'

To support decision-makers in the choice between the transport of water with a suitable quality from remote sources or the on-site treatment of water with a quality that needs to be adjusted, the water-network model and DESALT model were combined into the DEA-IWRM framework (Data Envelopment Analysis for Integrated Water Resource Management.

	TREATMENT MODEL	TRANSPORT MODEL	INTEGRATED MODEL
Name	DESALT (Wreyford et al., 2020)	WSN (Willet et al., 2020)	DEA-IWRM
Function	Determine different on-site treatment trains to supply desired water for industrial use based on available water quantity and quality.	Determine the optimal water transport network to supply water for industrial use based on cost minimization demand and availability.	Determine the preferred water supply designs based on desalination and transport, considering economic and environmental objectives.
Study Area	Dow	Zeeland	Dow and Zeeland
Performance Indicators	Unit production cost ($US/m^3) Specific energy use (kWh/m^3) CO_2-eq (kg CO_2-eq/m^3)	Transport costs (€/m^3) Specific energy use (kWh/m^3) CO_2-eq (kg CO_2-eq/m^3)	Total unit prod. cost ($US/m^3) Total specific energy use (kWh/m^3) Total CO_2-eq (kg CO_2-eq/m^3)

An overview of the functionalities of the DESALT model, the Water Supply Network model and the integrated DEA-IWRM framework.

Deltares

'We liked the interaction between research line 1 and research line 3 on the water supply network modelling approaches within Zeeuws-Vlaanderen for an important stakeholder within the Water Nexus consortium.'

The DEA-IWRM framework showed that the optimal distribution of combined treatment and transport for Dow Benelux in the Zeeuws-Vlaanderen region to ensure sufficient future water supply while considering environmental impacts is 20-30% treatment and 70-80% transport. New developments at Evides Industriewater and Dow Benelux B.V. illustrate how different water sources can be transported and treated by a treatment train of innovative water treatment technologies to supply process water from unconventional water streams:

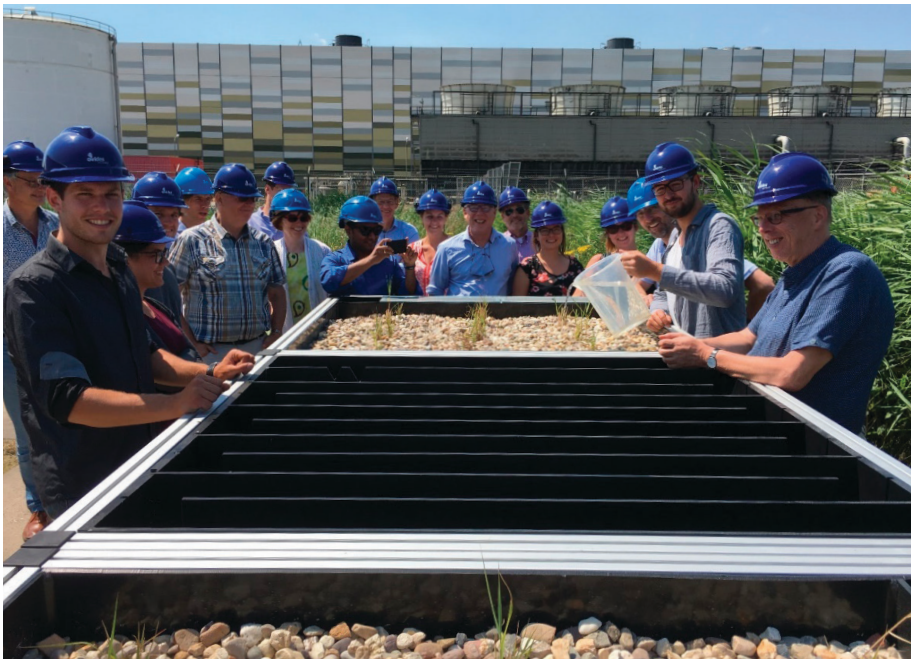
Evides Industriewater

'The Water Nexus research resulted in the development of a pilot scale wetland. By 2024 Dow Benelux BV and Evides Industriewater will implement a facility that allows the reuse of almost 8 million m³ annually of a mix of waters from various sources. Water will be supplied from the Terneuzen municipal treatment plant, Dow's wastewater treatment facility, and rainwater collected from the Dow premises and its periphery. Dow Benelux BV and Evides Industriewater have partnered with the Water Authority Scheldestromen in conducting a pilot-research, which consists of a constructed wetland as pretreatment followed by a brackish water line for the removal of salt and organic substances to produce a high quality process water.

In this treatment concept, aerated horizontal flow constructed wetlands are used to stabilize the effluent from the domestic and municipal WWTP's. On the whole, the wetlands are expected to enhance water quality towards the UF, IX and RO by reducing ammonium, suspended solids, organic carbon and nitrate. The concept works with an actively aerated reactor filled with expanded-clay granules, on which a biofilm grows. Reed is planted on top, but not considered essential for enhancing water quality. Harmful components are either degraded by the bacteria or accumulate in the wetland. Nitrification occurs in the aerated zones, denitrification in the non-aerated zones, provided there is sufficient carbon source.

The constructed wetland pilot has been running for a year now and the results are very positive. The removal of nutrients and therefore the biostabilisation of the water results in an easy to treat water and a successful concept.'

Official start of pilot constructed wetland experiments during a research line 3 meeting.



The Water Nexus pilot (on the left) & the spinoff (on the right).

Plant-e

'Implementation of Plant-MFCs in wetland systems can help monitoring important freshwater sources such as wetlands by providing power to sensor systems in remote areas. By implementing Plant-MFCs in (constructed) wetlands, but also ricefields, a major freshwater consumer in the world, this can potentially be combined with reduction of methane emissions that are otherwise associated with rice production and wetlands in general.'

From Water Nexus towards future fresh water management in delta areas

Shell Global Solutions B.V.

'A less tangible outcome of Water Nexus for Shell was the contribution to Shell's thinking around its sustainability commitments in the renewed Shell environmental strategy of Respecting Nature and resulting circularity studies for our operating assets.'

A key outcome of Water Nexus is the need to expand the water grid from serving one industry only to multiple water users in the full region requiring additional stakeholders and new governance approaches. At the end of 2019, the Water Nexus consortium invited representatives of other Dutch research programs focused on the future supply of fresh water in the Netherlands, such as Coastar and Lumbricus (see table below), for a brainstorm about tackling newly identified knowledge gaps as a result of these research programs in a new research initiative. The main observation of this session was that there is a mismatch in water demand and supply over the year in the Netherlands: Precipitation surpluses are discharged as fast as possible in winters, while high temperatures in the summer result in serious droughts and corresponding damage to agriculture, industry and nature. The traditional delta-strategy of the Netherlands – discharging water as fast as possible – needs to be adjusted to increase the fresh water availability during droughts. The research in Water Nexus, Coastar and Lumbricus has shown that local producer-to-consumer water grids, nature-based water buffering and treatment and technologies will urgently be needed to achieve this. This will include storing of wet-season surpluses and (re-)use of all water sources available, including currently ignored nonconventional water resources. These nonconventional water

COASTAR

Coastar

Coastal Aquifer Storage And Recovery – focusses on the use of subsurface solutions for a robust water supply and drought control by

- Closing the water gap between water supply and demand in space and time.
- Prevent salinization of ground/surface water by using brackish groundwater for fresh water production.

programma Lumbricus

Lumbricus

Focussed on the effectivity and interdependence of various measures to enhance the climate-robustness of soils and surface/ground water at the Higher Sandy Soils in the Netherlands. In addition, Lumbricus also focused on governance-related aspects, such as stakeholder responsibilities, societal costs and benefits and possibilities for valorisation.

resources, such as industrial and domestic effluents and brackish groundwater, are available year-round, and can help to overcome water shortages. This will constitute a major technical and societal transition.

KWR Water Research Institute

'Dealing with the fresh water – brackish water interface is challenging, but needed given the changing climatic conditions. Water Nexus provides relevant insights on how to anticipate on salt water intrusion in the root zone of agriculture crops and on the impact of salt water intrusion on the species composition of the natural vegetation. However, Water Nexus not only provides insights in the risks of salt water intrusion, but also on the opportunities to exploite brackish water.'

The proposed solution for safeguarding regional fresh water provision is a smart water-grid that facilitates regional self-sufficient water supply (so off the national grid and into a regional grid) by connecting current demand of water of certain minimal quality to available supply of that quality. To cope with fluctuations in natural water quantity and quality under weather variability and extremes, such a grid is supported by an increased underground storage capacity and the use of nonconventional and marginal (brackish, effluent) water resources after treatment including energy efficient desalination. To design and operate such a grid, different types of technologies are needed, that build upon the technologies that were developed in Water Nexus:

- Digital technologies (modelling of the natural system and storage impacts, system models to design and optimize the grid), building on the regional modelling performed in research line 1.1 and the system level modelling developed in Water Nexus research line 3.
- Physical/chemical and nature-based technologies for water and brine treatment and water quality monitoring, building on the treatment-technologies developed in Water Nexus research lines 2.3 and 3 and frameworks for the assessment of the effect of contaminants in ecosystem developed in research line 1.2.

Deltares

A future research program that studies robust fresh water management should include:

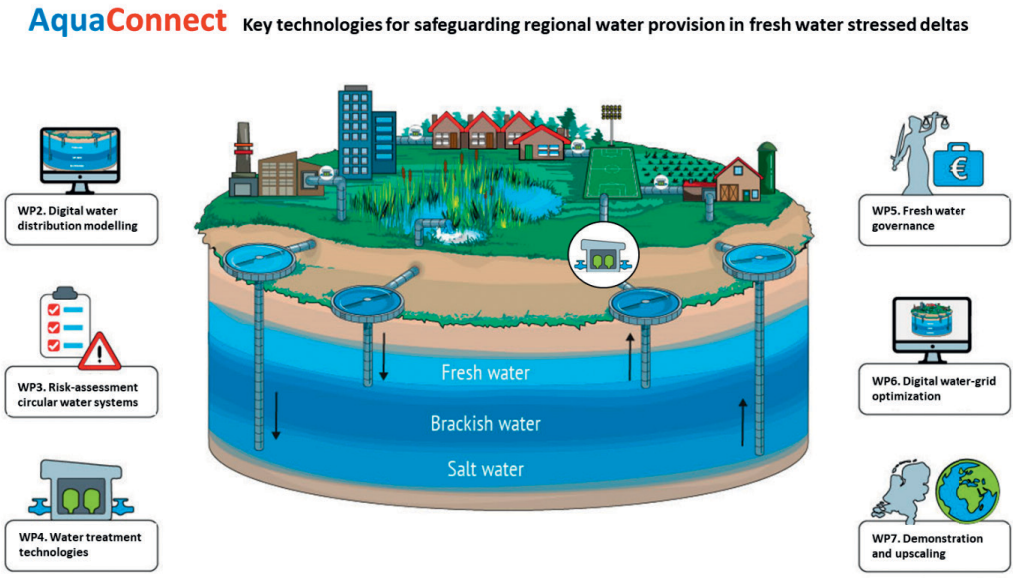
- *Integration of the different successful Water Nexus water management components (treatment technologies, wast water, desalinisation using brackish groundwater, etc.) within a logical framework, robust enough that can be allied in different water scarcity settings around the world.*

- *Smarter fresh surface and groundwater management in a hour-to-hour (surface water) and/or day-to-day (groundwater) operational setting, to be implemented e.g. at water boards and drinkingwater companies.*
- *A computational toolbox to estimate the gap between water supply and demand over time and space (water misbalance), on how to fill this gap by different cost-efficient water strategies, such as water savings in households, industry and especially agriculture, subsurface water storage (e.g. COASTAR concept), waste water use, land use change (salt-resistent crops), smarter groundwater extractions.*

In addition to these technological advances, it is essential to overcome economic, governance and legal and cultural/perception boundaries to be able to make the transition towards a water-retaining delta. The need for enhanced knowledge in these fields – digital technologies, physical/chemical treatment technologies and governance tools – has led to the design of a new NWO-TTW funded research program: AquaConnect.

AquaConnect will consider the entire water system, including buffers, infrastructure, users and prosumers, and the management of that system through governance and infrastructures, which are supported by adequate data, treatment and knowledge about boundary conditions and legal, societal and economic constraints. As a result of the Water Nexus, Coastar and Lumbricus research, several scientific and applied knowledge gaps were identified, that will be studied in AquaConnect:

- Unclear and uncertain a) availability of nonconventional water sources, b) potential of subsurface water storage, c) possibilities for the water network for delivering water from the supplier to the user, and d) dynamics of brackish water extraction and underground brine disposal.
- Unknown quality requirements for different water re-use schemes in a circular – re-use based – water system, associated with a lack of cost effective technologies for treatment that can tailor quality to these requirements and prevent new problems with brines and sludges.
- A lack of insight in the economic value of freshwater availability for regional economics, appropriate and effective governance and legal arrangements, and societal/cultural dynamics relevant for upscaling.
- A lack of design instruments to test the feasibility and economics of adaptations in local water infrastructure (smart water grids, infrastructure needed to bring the water from sources to the end users in industry, agriculture or nature conservation).
- A lack of integrated demonstrations with stakeholder inclusion, which is the most convincing tool for further integration, national upscaling and international outreach.



An overview of the research work-packages in AquaConnect.

In AquaConnect, 13 new PhD students and 5 postdocs at different universities will work in 5 different scientific research work packages that build upon the knowledge generated in Water Nexus. This scientific research will be performed in strong collaboration with a large consortium of end-users, among which are drinking water companies, industrial end-users, water authorities, national, regional and local authorities, technology providers, consultancies, research institutes and umbrella organizations, of which many also participated in Water Nexus. The relation between the AquaConnect work packages and Water Nexus research lines is highlighted in the table on the next spread.

	Objective of AquaConnect work package	Building on Water Nexus
Work package 2 Digital water distribution modelling	• To develop seamlessly scalable (between regional and local scale) groundwater-surface water models including salinity that calculate current and future subsurface water distribution and storage possibilities. • To experimentally determine the effect of brackish water extraction on subsurface water distribution. • To design a generic toolbox to support the management of underground water storage and extraction by data-model assimilation.	Research line 1.1
Work package 3 Risk-assessment of circular water systems	• To experimentally determine the fate of chemicals in groundwater systems used for water storage. • The development of risk-assessment strategies that can identify potentially harmful chemicals in cyclic water systems. • To assess the impact of water reuse instead of discharge on biodiversity.	Research line 1.2
Work package 4 Water treatment technologies	• To develop a electrodialysis/ nanofiltration configuration that selectively removes target chemicals from divers water streams. • To broaden currently existing sustainability frameworks with newly identified chemicals of risk in circular water systems using modelling and field-experiments that predict the quality effects of reusing or disposing residual streams on soil and groundwater.	Research lines 1.2, 2.3

	Objective of AquaConnect work package	Building on Water Nexus
Work package 5 Fresh water governance	• To develop models and calculate the economic value of freshwater for the regional economy. • To map policy and legal frameworks that guide water provision in a comprehensible way. • To develop insight in frameworks that exist elsewhere on the global and that secure economic viability, ecological integrity and societal perceptions issues. • To study how upscaling issues (including perception) have been addressed elsewhere to upscale technologies.	Identified as an important missing link in Water Nexus
Work package 6 Digital water grid optimization	• To develop a decision-support tool for water-grid optimization that can generate a climate-robust water system, based on new water sources, associated risks, new technology and institutional, socio-economic and legal constraints. • To develop a monitoring and closed-loop control framework for local smart water-grids based on distributed model predictive control and artificial intelligence. • To develop a decision-support tool for regional authorities that allows regional redesign to include all potential water users, including the environment.	Research lines 1.1, 1.2, 2.1, 2.3 and 3

An inventory among the Water Nexus end-users to identify possible points of improvement to take along from Water Nexus to AquaConnect has shown that the connection between the scientific research and actual application of the results obtained in Water Nexus was not strong enough, and will be crucial in future large research programs. In addition, emphasis should be paid to the integration of the results of the individual scientific researchers in integrated concepts for future fresh water management:

Dow Benelux B.V.

'The tighter connection between academia, end-users, and public parties should receive more emphasis and commitment from all sides to establish a living lab environment on regional scale.'

Evides Industriewater

'In Water Nexus many PhD research projects have been done. In future programmes more effort should be put in combining all that research to one joint overall conclusion.'

Royal HaskoningDHV

'Water Nexus covered many different research aspects and during the program we noticed a few times that integration of all the results was sometimes a big hurdle. Finally we succeeded but it is crucial from the beginning that integration takes place.'

TNO

'The programme was too large, which made the preparation and overhead expensive and time consuming, and this was not compensated by extra results from cross fertilization between the partners and projects.'

Witteveen+Bos

'Valorisation of research results was very limited: Pragmatic and applicable solutions and the translation from research to practice was missing. No budget and time was reserved in the programme.'

Shell Global Solutions B.V.

'Insights into design rules for actual products developed by participants and/or specific projects within Shell should be included in future research programs, such as Water Nexus.'

Taking into account the advice of the Water Nexus end-users, the research in the scientific work packages will be connected to demonstration pilots in four different Dutch regions – Zeeuws-Vlaanderen, Province of South-Holland, the Amsterdam region and the Higher Sandy Soils, and internationally, to ensures the transfer of scientific output -insights and technical innovation- to outcome in practice through demonstration and further implementation in practice parallel to the program. Parallel to Water Nexus, a twinning project was performed in the NWO program Urbanizing Deltas of The World, with project name ENTIRE – ENabling susTainable Industrial development in Vietnamese delta's, REducing, recycling and multi-sourcing industrial water. ENTIRE was oriented on developing a sustainable and circular water provision for industries located in Industrial Zones in the region of Ho Chi Minh City in Vietnam, and was also performed from 2015 to 2021. Many ideas of Water Nexus and ENTIRE were exchanged, and the collaboration build in ENTIRE between the partners from Vietnam and the Netherlands will be continued in the international outreach part of the new AquaConnect program. With this international connection, we continue to help to establish -solid science and technology based- climate robust water provision, not only in The Netherlands, but also in other delta's in the world.
The pathway of impact of AquaConnect will depart from the scientific and applied research questions concerning robust future fresh water management in these regions, and aims to develop, through thorough interaction with the regional stakeholders and an emphasis on the integration of the scientific results, the following outcomes:

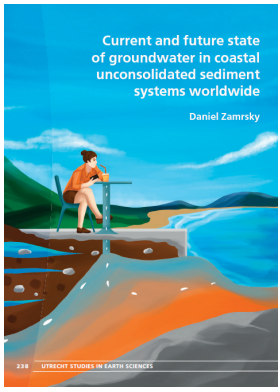
- A framework for institutional collaboration and interaction for circular water approaches.
- Explicit business cases enhancing economic and social drive to develop and implement nonconventional water based smart water-grids.
- A regulatory base for the use of nonconventional water resources, and sustainable management of brines and sludges.
- Nonconventional water sources are accepted and implemented as important part of a drought-resistant water provision system.
- A portfolio for nonconventional water sources based smart water-grids is showcased and ready to expand in Dutch, European and global markets.

5
Overview of Water Nexus scientific publications

At the time of compiling this brochure, the Water Nexus scientific research has led to 45+ peer-reviewed open access scientific publications, and the completion of different doctoral theses:

Research line 1.1 Resource analysis and regional water management

- King, J., Oude Essink, G.H.P., Karaoulis, M., Siemon, B., Bierkens, M.F.P. (2018). Quantifying geophysical inversion uncertainty using airborne frequency domain electromagnetic data - applied at the Province of Zeeland, the Netherlands, *Water Resources Research 54*, 8420- 8441.
- King, J.A., Oude Essink, G.H.P., Karaoulis, Marios, Bierkens, M.F.P. (2020). A practical quantification of error sources in regional-scale airborne groundwater salinity mapping, *Environmental Research Letters 15*, 13 p.
- Van Engelen, J., Verkaik, J., King, J., Nofal, E., Bierkens, M.F.P., Oude Essink, G.H.P. (2019). A three-dimensional palaeohydrogeological reconstruction of the groundwater salinity distribution in the Nile Delta Aquifer, *Hydrology and Earth System Sciences 23*, 5175-5198.



- Zamrsky, D., Oude Essink, G.H.P., Bierkens, M.F.P. (2018). Estimating the thickness of unconsolidated coastal aquifers along the global coastline, *Earth System Science Data 10*, 1591-1603.
- Zamrsky, D., Karssenberg, M., Cohen, K.M., Bierkens, M.F.P., Oude Essink, G.H.P., (2020). Geological heterogeneity of coastal unconsolidated groundwater systems worldwide and its influence on offshore fresh groundwater occurrence, *Frontiers in Earth* Science 7.
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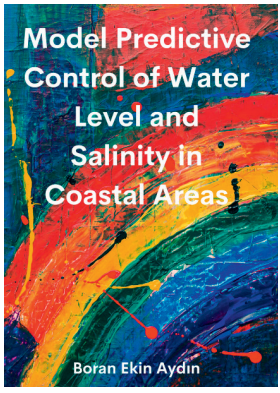

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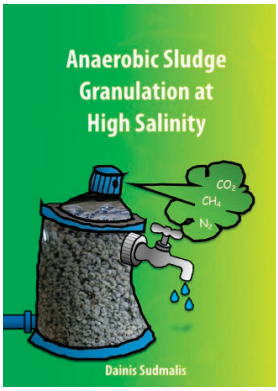

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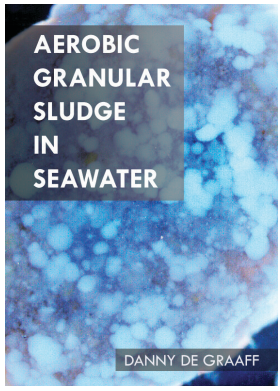

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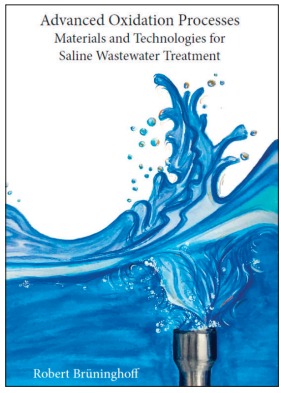

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Advanced oxidation processes for organic compounds removal in saline conditions: Possibilities and limitations

Pradip Saha

Plant Microbial Fuel cell: Mechanistic characterization & application in natural and constructed wetlands

Pim de Jager

Research line 3 – Integral blue prints

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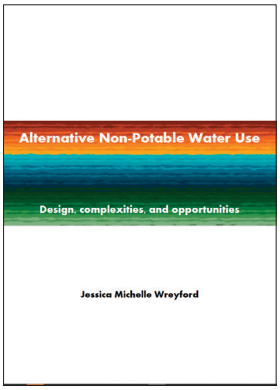
Alternative water resources for industry: Designing environmentally compatible regional supply networks

Joeri Willet



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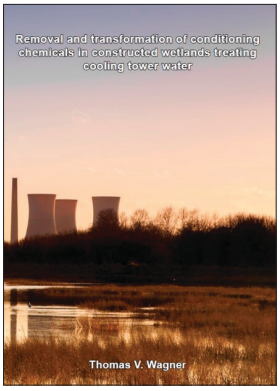

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