ETM Case study 1: Salt and urban water as a resource

Summary

Shortage of fresh water is increasingly damaging industrial, agricultural, and drinking water sectors and ecosystems, especially in delta areas suffering from climate change driven droughts. Industrial companies consume large amounts of fresh water, and have adopted sustainability policies aiming at reducing their fresh water footprints. ETM researchers led the past five years the Water Nexus consortium of industries, research institutes, technology developers, consultancies, governing institutions and universities, to help industry to use treated salt wastewater and brackish groundwater as a resource, instead of fresh water. Various examples from practice were provided by industrial stakeholders as a starting point for the development of modelling tools and technological treatment trains to enable salt water (re)use. Modelling tools were designed to support circular water management in industries and the sustainable extraction of brackish water from the subsurface for industrial use. One treatment train was developed for highly saline industrial effluent rich in organic material, and another for treating moderately saline wastewater and reusing the treated water in industry, i.e. for cooling towers, or in agriculture. Seven ETM PhD and Postdoc researchers joined this co-creative environment and while co-designing efficient and scalable solutions, they obtained new scientific insights in the mechanisms underlying a variety of water treatment technologies and water grid models. This practice-science connectivity yielded technological and modelling outcomes that are now used in practice, 30 scientific publications, inclusion of new scientific modelling and technological principles and practical examples in student courses and 40 BSc/MSc graduation theses.

Background

Urbanized delta's around the world, such as the Netherlands, Southern Vietnam and Bangladesh, experience increasing fresh water scarcity problems. This is the result of increased water consumption, climate change related droughts and saltwater intrusion. This results in seasonal fresh water shortages for ecosystems, agriculture, industry and even municipalities, leading to increasing economic and ecological damage. We aimed to evoke a paradigm shift in water sourcing and use, i.e. to consider saline (waste) water no longer as a threat but as an alternative water source, alleviating the pressure on fresh water resources. (Re)using saline water, and other alternative water resources such as rainwater or wastewater treatment plan effluents requires innovative technological solutions and strong collaboration with industries, consultancy companies, drinking water companies, technology developers and government. In a co-creative way, this group of stakeholders and scientists selected three domains that demand new knowledge and tools to enable the use and reuse of salt water and other alternative waters as a resource:

1. **Modelling tools for use of salt water and other alternative water resources** were identified as lacking, and these are needed to support salt water reuse and circular water management.

Technologies for treatment of saline industrial wastewaters with

2. **high amounts of organics**. These are often encountered in dairy, leather, and textile industries.
3. **low amounts of organics**. These are often found in cooling tower draw down and produced waters in chemical and petrochemical industries.

Research objectives

The research objective of Water Nexus was to provide blueprints for future water management based on the use of saline water in fresh water stressed delta-areas using situations from practice provided by the consortium partners as living lab studies. These blueprints integrated new models, tools and combined water treatment technologies (technology trains) that allow matching the demand and supply of water between water users and water producers, in quantity and quality.

Research approach

Various examples from practice from industrial sectors consuming large volumes of water with different characteristics formed the basis for the development of new technologies for saline water treatment and re-use management. The providers of the examples from practice, and Water Nexus partners grouped together to co-create innovative technologies for saline water treatment and modelling tools for circular water management, on three main topics:

1. Modelling tools for use of salt water and other alternative water resources*:* In these studies, the fresh water scarce region of Zeeuws-Vlaanderen (The Netherlands) is taken as the practical example. Currently, millions of m^3 of fresh water per year are imported to this region but this supply has become uncertain due to increasing droughts occurring in the whole Rhine-Meuse-Scheldt delta region. Alternative resources such as brackish groundwater and collected residential rainwater can ensure, at least partially, the provision of water to local water users, such as industries as DOW Benelux, or agriculture. Therefor a toolbox was developed to model and design such alternative resource based water grids. One tool connects available water sources, including brackish groundwater, with water users, considering both water quantity and quality requirements. Herein limits for extraction were taken into account to prevent damage to nature and salt water intrusion from the sea. Local decentralized water supply networks were designed using the model, connecting users with fresh and brackish groundwater sources (Fig. 1).

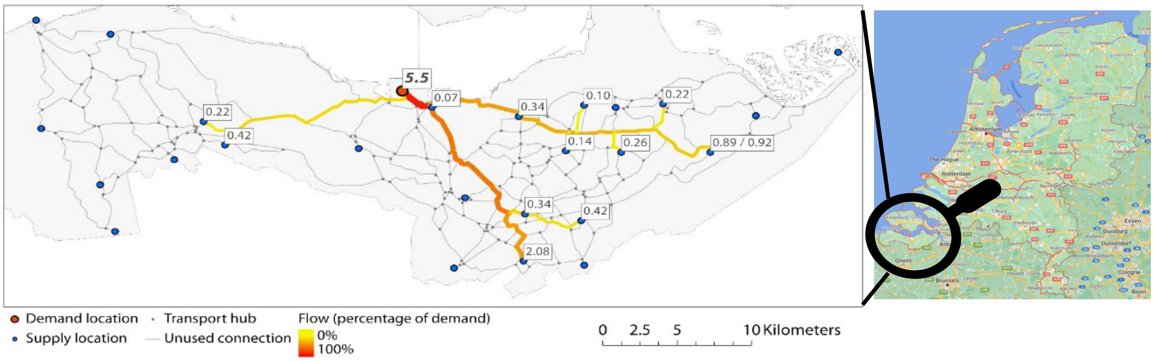

Figure 1: Regional water supply network (smart water grid). The model selects available water sources, considering available water quantity and quality and regional landscape characteristics, and calculates the required pipeline infrastructure for the lowest costs.

The second tool designs water treatment trains, based on water quality requirements of the users, and the quality of available sources. These trains are receiving increased interest for their potential to meet water standards while minimizing negative externalities. However, determining which technologies to combine and predicting their performance is both difficult and situation/context specific. We developed a tool to compare desalination treatment trains based on the same input requirements.

2. Technology train for saline industrial wastewaters with high amounts of organics*.* The wastewaters generated by many agro-industrial sectors often contain high concentrations of both salt and dissolved organic materials. To consider these streams for further re-use, firstly the organic pollutant level needs to be decreased. Typically for highly saline wastewaters this is done via physical-chemical and/or aerobic biological processes that are disadvantageous since these require high amounts of energy and/or chemicals. A more sustainable alternative would be the application of compact anaerobic bioreactors, as first step in a treatment train. In this process microorganisms convert the organic pollutants into an energy rich biogas consisting mainly of methane (CH_4) and carbon dioxide (CO_2) and little amount of energy is required for operation. However, salts negatively impact microorganisms activity and granulation, hampering anaerobic treatment of saline waters. The ETM team proved that these two problems can be resolved, which was achieved by tuning the process conditions of lab-scale reactors at ETE and linking the reactor performance with a thorough analysis of microbial communities developing in them by MIB (Fig. 2).

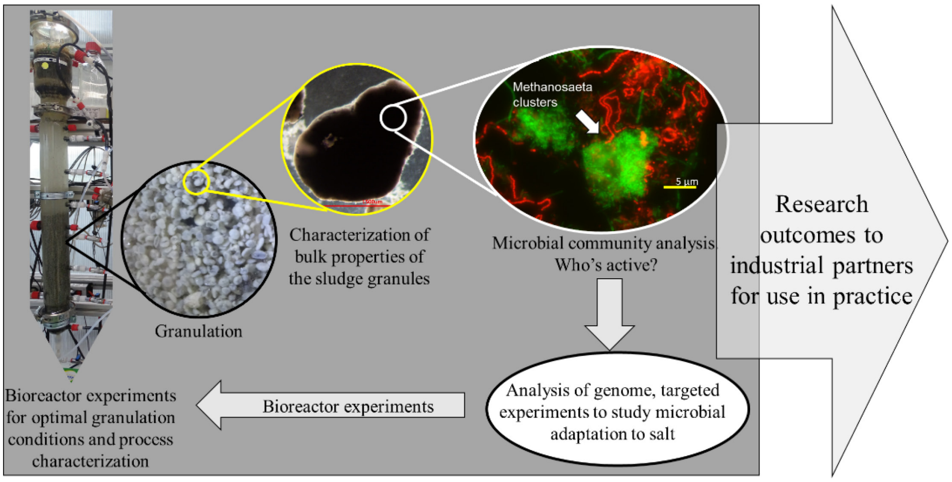

Figure 2: Research that made anaerobic granular sludge technology work for waters with high salinity.

Successful granulation, together with mechanistic insights into microbial adaptation to salt, allowed to improve two full-scale treatment plants in operation in cooperation with technology developers Paques, Nijhuis Industrial Technologies and Royal Haskoning-DHV. An energy efficient technology train of a set of Anaerobic-Aerobic granular sludge reactors was designed in collaboration with Delft University of Technology, one of the other university partners of Water Nexus.

3. Technology train for saline industrial waste waters with low amounts of organics. During cooling, water is sprayed at the top of a cooling tower and largely evaporates; the water that remains at the bottom is enriched in salt. To make this wastewater reusable, industrial conditioning chemicals and natural organic compounds need to be removed and followed by desalination. The optimal set of technologies for such a treatment train was not available at the start of the project. Therefore various technologies were tested by the ETM team of researchers, in collaboration with Dow Benelux, Evides Industrial Water, Plant-E, Magneto and Wageningen Food & Biobased Research. The first technology tested was a constructed wetland to remove conditioning chemicals from the cooling tower wastewater. Various different conditions and configurations were investigated in the ModuTech facility of ETM in Wageningen, using artificial wastewater, and effective removal of conditioning chemicals was demonstrated. This led to the design of a constructed wetland pilot, that was installed and operated on-site next to the cooling tower of DOW Benelux in Terneuzen, and which was tested for its ability to remove organic conditioning chemicals from the cooling tower wastewater in practice (Fig 3).

Figure 3: Constructed wetland pilot in Terneuzen, the Netherlands, effectively removing conditioning chemicals from cooling tower wastewater.

Further steps in the treatment of the cooling tower wastewater are needed to make reuse possible. Many investigations at ETE and with other Water Nexus partners resulted in a coupling of different processes and the design of a treatment train, using newly developed nanofiltration membranes (Fig. 4). The concentrate stream of the nanofiltration was subjected to electrochemical oxidation to remove organic carbon, and the permeate was fed to a reverse osmosis process to desalinate the water and make it ready for reuse in the cooling tower.

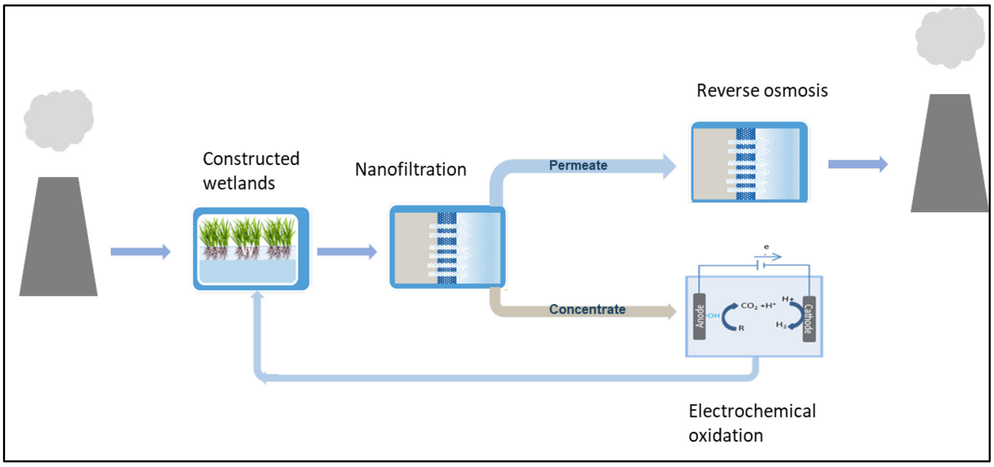

Figure 4: Technology train developed with and tested for Dow Benelux, to make cooling tower wastewater reusable.

This integrated set of technology studies provided essential insights in relevant process parameters of the different steps of treatment. Such a process scheme can be used for making cooling tower wastewater reusable, as was demonstrated in practice at the site of DOW Benelux. A technology set of a similar scheme can make water streams from petrochemical (and other) industries suitable, for instance, for irrigation in (non-food) agriculture. This is currently further investigated for "greening the desert" programs in the Middle East in collaboration with Shell and local universities.

Stakeholder involvement

Solving water scarcity challenges requires close interaction with stakeholders to ensure that the solutions designed by our ETM researchers match the needs of society. Input at the start of research, feedback during the research, and demonstration of research outcomes of the newly developed models, tools and technologies, is essential for conducting high level science as well as realizing societal impact. In our approach, we took the water footprint reduction and water reuse needs of the large industrial water users, such as Dow Benelux and Shell, and drinking water companies, such as Evides Industrial Water and Oasen, as starting point. The development of water treatment technologies was done in collaboration with technology providers, such as Paques, Nijhuis Technologies, Magneto and Plant-E. The translation of scientific insights to broader application of the modelling and blueprint concepts was facilitated by consultancy companies, such as Witteveen&Bos and RoyalHaskoning-DHV, and research institutes, such as Deltares, TNO and KWR-Water. Governmental organizations, such as the Ministry of Infrastructure and Water Management, provinces and water authorities provided insight in the legal and administrative boundaries for implementing the newly developed technologies in blueprints for future water management.

Link to education

Central to fighting water scarcity, is educating future water practitioners on how to perform academic research on societally relevant challenges. We aim to educate PhDs, MSc, and BSc students on how to execute high-level academic research in conjunction with stakeholders in order to make high societal impact. In line with this vision, we organised so-called design studio workshops with PhD's, Postdocs and relevant stakeholders. These workshops were held at several places and occasions, including the offices of the local Water Authority "ScheldeStromen" in Terneuzen and the main office of Shell in Amsterdam. In this way PhD students learn how to interact with their societal counterparts, to understand and listen to them and take their suggestions into consideration, while at the same time holding on to scientific and integrity principles. These stakeholder aspects are also incorporated in the education programs of Environmental and Biobased Sciences at WUR at BSc and MSc level.

Research Highlights

Currently the Water Nexus research has resulted in 19 peer-reviewed scientific publications involving ETM researchers (Appendix 1a), while a dozen more publications is expected in the coming year. An important research highlight is that both the modelling tool box (1) for designing smart water grids using alternative water resources, and the physical-chemical treatment trains (2), were recognized by 37 stakeholders as very important instruments for making the Netherlands resilient against drought. This recognition appeared in their support for the new and awarded NWO grant AquaConnect (with a budget of 6.5 M€). A second highlight is the Anaerobic Granular Sludge technology (3) for treating salt water with high loads of organics bringing groundbreaking new scientific insights on how the granular sludge microorganisms protect themselves against salinity, awarding researcher Dainis Sudmalis the prize for best presentation at the renowned 'IWA Granular Sludge' conference in 2018. A third highlight are the emerging worldwide possibilities for reuse of alternative water resources with lower amounts of organics (4) after treatment. Especially constructed wetlands combined with other technologies have proven to be very cost-effective in cleaning water containing harmful and difficult to degrade chemicals.

Societal Impact

Water Nexus stakeholder interactive research has broadened the spectrum for the application of various water treatment technologies towards more saline effluent streams, and delivered new models and tools that allow regional water self-sufficiency. The enhanced understanding of salt-adapted granular sludge applications has led to the full-scale application of these developments by providers of technology for industrial wastewaters with high amounts of organic pollutants. Newly developed technologies for cooling tower water treatment are currently being considered for use in actual cooling tower water treatment trains, and similar treatments for making such water streams suitable for irrigative agriculture. The value of nature-based water treatment by constructed wetlands has been acknowledged by large industrial water users, which are currently looking into new locations with different wastewater streams for implementation. The decision-making frameworks for regional water extraction, transport and local treatment in Zeeuws-Vlaanderen are now being adopted by the local stakeholders, while also stakeholders from other regions in the Netherlands and worldwide have shown great interest in applying these elsewhere. Via various global outreach projects (Appendix 1b), technology trains with wetland components are now being developed to make water suitable for reuse in industry or for irrigative agriculture. Currently we investigate with local stakeholders such treatments for industrial zones in Vietnam, for the Barapullah drain in New Delhi, India, for the greening the desert programs in Oman and Qatar, and for the city of Khulna in Bangladesh (Fig. 5).

Figure 5: Rice paddy field near Khulna City Bangladesh, threatened by salt water intrusion, that could greatly benefit from treated urban grey water as a fresh water resource.

Appendix 1a *Peer-reviewed* scientific publications involving ETM researchers resulting from the program Water Nexus

Bianchi, A. B., Wreyford, J. M., Willet, J., Gerdessen, J. C., Dykstra, J. E., and Rijnaarts, H. H. M. (2021) Treatment vs. transport: A framework for assessing the trade-offs between on-site desalination and off-site water sourcing for an industrial case study. Journal of Cleaner Production, **285**, 124901. [online] https://www.sciencedirect.com/science/article/pii/S0959652620349453.

Brüninghoff, R., van Duijne, A. K., Braakhuis, L., Saha, P., Jeremiasse, A. W., Mei, B., and Mul, G. (2019) Comparative Analysis of Photocatalytic and Electrochemical Degradation of 4-Ethylphenol in Saline Conditions. Environmental Science & Technology, **53**(15), 8725–8735. [online] https://doi.org/10.1021/acs.est.9b01244.

Gagliano, M. C., Sudmalis, D., Pei, R., Temmink, H., and Plugge, C. M. (2020) Microbial Community Drivers in Anaerobic Granulation at High Salinity. Frontiers in Microbiology, **11**, 235. [online] https://www.frontiersin.org/article/10.3389/fmicb.2020.00235.

Gagliano, M. C., Sudmalis, D., Temmink, H., and Plugge, C. M. (2020) Calcium effect on microbial activity and biomass aggregation during anaerobic digestion at high salinity. New Biotechnology, **56**, 114–122. [online] https://www.sciencedirect.com/science/article/pii/S1871678419301189.

Gagliano Maria C., Neu, T. R., Kuhlicke, U., Sudmalis, D., Temmink, H., and Plugge, C. M. (2018) EPS Glycoconjugate Profiles Shift as Adaptive Response in Anaerobic Microbial Granulation at High Salinity. Frontiers in Microbiology, **9**, 1423.

Saha, P., Bruning, H., Wagner, T. V, and Rijnaarts, H. H. M. (2020) Removal of organic compounds from cooling tower blowdown by electrochemical oxidation: Role of electrodes and operational parameters. Chemosphere, **259**, 127491. [online] https://www.sciencedirect.com/science/article/pii/S0045653520316854.

Saha, P., Wagner, T. V, Ni, J., Langenhoff, A. A. M., Bruning, H., and Rijnaarts, H. H. M. (2020) Cooling tower water treatment using a combination of electrochemical oxidation and constructed wetlands. Process Safety and Environmental Protection, **144**, 42–51. [online] https://www.sciencedirect.com/science/article/pii/S0957582020316207.

Sudmalis, D., Gagliano, M. C., Pei, R., Grolle, K., Plugge, C. M., Rijnaarts, H. H. M., Zeeman, G., and Temmink, H. (2018) Fast anaerobic sludge granulation at elevated salinity. Water Research, **128**, 293–303. [online] https://www.sciencedirect.com/science/article/pii/S0043135417308758.

Sudmalis, D., Millah, S. K., Gagliano, M. C., Butré, C. I., Plugge, C. M., Rijnaarts, H. H. M., Zeeman, G., and Temmink, H. (2018) The potential of osmolytes and their precursors to alleviate osmotic stress of anaerobic granular sludge. Water Research, **147**, 142–151. [online] https://www.sciencedirect.com/science/article/pii/S0043135418307917.

Sudmalis, D., Mubita, T. M., Gagliano, M. C., Dinis, E., Zeeman, G., Rijnaarts, H. H. M., and Temmink, H. (2020) Cation exchange membrane behaviour of extracellular polymeric substances (EPS) in salt adapted granular sludge. Water Research, **178**, 115855. [online] https://www.sciencedirect.com/science/article/pii/S0043135420303924.

Wagner, T. V., Helmus, R., Becker, E., Rijnaarts, H. H. M., De Voogt, P., Langenhoff, A. A. M., and Parsons, J. R. (2020) Impact of transformation, photodegradation and interaction with glutaraldehyde on the acute toxicity of the biocide DBNPA in cooling tower water. Environmental Science: Water Research and Technology, **6**(4), 1058–1068.

Wagner, T. V., Parsons, J. R., Rijnaarts, H. H. M., de Voogt, P., and Langenhoff, A. A. M. (2018) A review on the removal of conditioning chemicals from cooling tower water in constructed wetlands. Critical Reviews in Environmental Science and Technology, **48**(19–21), 1094–1125. [online] https://doi.org/10.1080/10643389.2018.1512289.

Wagner, T. V, Al-Manji, F., Xue, J., Wetser, K., de Wilde, V., Parsons, J. R., Rijnaarts, H. H. M., and Langenhoff, A. A. M. (2021) Effects of salinity on the treatment of synthetic petroleum-industry wastewater in pilot vertical flow constructed wetlands under simulated hot arid climatic conditions. Environmental Science and Pollution Research, **28**(2), 2172–2181. [online] https://doi.org/10.1007/s11356-020-10584-8.

Wagner, T. V, Helmus, R., Quiton Tapia, S., Rijnaarts, H. H. M., de Voogt, P., Langenhoff, A. A. M., and Parsons, J. R. (2020) Non-target screening reveals the mechanisms responsible for the antagonistic inhibiting effect of the biocides DBNPA and glutaraldehyde on benzoic acid biodegradation. Journal of Hazardous Materials, **386**, 121661. [online] https://www.sciencedirect.com/science/article/pii/S0304389419316152.

Wagner, T. V, Parsons, J. R., Rijnaarts, H. H. M., Voogt, P. De, and Langenhoff, A. A. M. (2020) Benzotriazole removal mechanisms in pilot-scale constructed wetlands treating cooling tower water. Journal of Hazardous Materials, **384**(July 2019), 121314.

Wagner, T. V, de Wilde, V., Willemsen, B., Mutaqin, M., Putri, G., Opdam, J., Parsons, J. R., Rijnaarts, H. H. M., de Voogt, P., and Langenhoff, A. A. M. (2020) Pilot-scale hybrid constructed wetlands for the treatment of cooling tower water prior to its desalination and reuse. Journal of Environmental Management, **271**, 110972. [online] https://www.sciencedirect.com/science/article/pii/S0301479720309002.

Willet, J., King, J., Wetser, K., Dykstra, J. E., Oude Essink, G. H. P., and Rijnaarts, H. H. M. (2020) Water supply network model for sustainable industrial resource use a case study of Zeeuws-Vlaanderen in the Netherlands. Water Resources and Industry, **24**, 100131. [online] https://www.sciencedirect.com/science/article/pii/S221237172030024X.

Willet, J., Wetser, K., Vreeburg, J., and Rijnaarts, H. H. M. (2019) Review of methods to assess sustainability of industrial water use. Water Resources and Industry, **21**, 100110. [online] https://www.sciencedirect.com/science/article/pii/S2212371718300404.

Wreyford, J. M., Dykstra, J. E., Wetser, K., Bruning, H., and Rijnaarts, H. H. M. (2020) Modelling framework for desalination treatment train comparison applied to brackish water sources. Desalination, **494**, 114632. [online] https://www.sciencedirect.com/science/article/pii/S0011916420313102.

Appendix 1b Global outreach projects where technology trains with wetland components are developed

- Water Nexus (https://waternexus.nl/)
- Entire (https://www.nwo.nl/en/projects/w-0769202)
- LOTUSHR (https://lotushr.org/)
- Water2Rice project of Kamonishish Haldar (https://www.wur.nl/en/Research-Results/Research-programmes/International-programmes/Asia/Bangladesh.htm)
- Greening the Desert (https://www.shell.com/about-us/major-projects/pearl-gtl/producing-water-in-the-desert.html; https://www.shell.com/inside-energy/oman-reed-beds-nature.html#vanity-aHR0cHM6Ly93d3cuc2hlbGwuY29tL3N1c3RhaW5hYmlsaXR5L2Vudmlyb25tZW50L3dhdGVyL2EtbmF0dXJhbC1maWx0ZXItZm9yLXdhdGVyLXRoZS1uaW1yLXJlZWQtYmVkcy5odG1s)
- AquaConnect >> NWO/Min EZ website 10th of March