



7 INNOVATION IN WATER SINGAPORE

An R&D publication of PUB, Singapore's national water agency | June 2015 | Volume 7



Thank you for picking up the latest edition of Innovation in Water | Singapore. We hope you will enjoy reading all about some of the latest, cutting-edge water research carried out in Singapore.

PUB, Singapore's national water agency, welcomes research collaborations that are in line with our mission: to ensure an adequate, efficient and sustainable supply of water.

There are opportunities for collaborative research abound for partners in the water and related industries, universities and research institutions (locally and overseas), as well as for creative individuals who share our objective of improving water supply management through use-inspired fundamental research, application and technological development, as well as investment in process improvement, knowledge management and implementation.

R&D online portal SINGwater

To support this endeavour, PUB has launched the Singapore INnovation Gateway for Water (SINGwater), an R&D online portal. SINGwater enables interested researchers to find out about PUB's key research initiatives and collaboration opportunities, such as funding support and test-bedding of technologies at PUB's facilities, as well as submit new R&D proposals. PUB's research collaborators can also manage ongoing projects via SINGwater.

With this new portal, PUB hopes to foster closer interaction with its research partners and invite innovative ideas from around the world.

To begin your partnership with PUB, log on to SINGwater at pubwaterresearch.com.sg and create a general user account. For other enquiries, contact us at pubwaterresearch.com.sg/ContactUs.aspx.



CONTENTS

- Introduction**
- 3 Message from the Executive Director
- Editorial**
- 4 Harnessing innovation for a water-secure future
- Feature**
- 6 Moving towards energy self-sufficiency in used water treatment
- People in Water Research**
- 9 Orange County Water District
- Facilities Focus**
- 10 Improving NEWater plant operations
- Research Highlights**
- Intelligent Watershed Management**
- 14 Polishing stormwater runoff through bioretention systems
- 15 Using SWAN to monitor water quality in reservoirs
- 16 Water in drains gets a clean-up
- Membrane Technology**
- 18 Improving membrane permeability by mimicking nature
- 19 Using chemistry to improve membrane performance
- 20 Recovering water from desalination brine
- Network Management**
- 22 Solving the mystery of biofilm growth in pipes
- 23 Intelligent technologies to reduce water leakage in pipes
- 24 Monitoring cyanide in used water
- Used Water Treatment**
- 26 Treating municipal used water using anaerobic systems
- 27 Closing the industrial water loop
- 28 Real-time aeration control system to lower energy footprint in used water treatment
- Water Quality and Security**
- 30 Measuring toxins released by dead bacteria
- 31 Investigating environmental controls of blue-green algae in reservoirs
- 32 Monitoring of organic compounds goes 'live'
- Water Treatment**
- 34 Carbon filters remove micropollutants in water
- 35 Maximising water recovery from used water reclamation
- 36 Ceramic membranes improve water treatment processes
- 37 **PUB Collaborators**

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We pave the way for water innovation

At the **Environment and Water Industry Programme Office (EWI)**, our mission is to nurture and grow the water industry in Singapore. Through EWI's multi-agency efforts, Singapore has been transformed into a Global Hydrohub supporting a vibrant water eco-system. We believe that technology is the key to continued growth in the water industry and we pave the way by offering a variety of avenues to support research and development in water technologies. These range from research funding, and PhD scholarships to offering facilities for companies to test-bed potential breakthrough technologies and solutions.

Let us help bring your innovations to fruition. Visit www.pub.gov.sg/ewi today to find out more about our schemes.



Message from the Executive Director

Singapore currently consumes 400 million imperial gallons of water daily. This is about 720 Olympic-size swimming pools full of precious H₂O.

As industry and commerce grow, and our population increases, demand for water will also go up. PUB expects that total demand for water will double by 2060.

This is water that we do not have now. Water we will need to find and to treat.

If we just do more of the same, the next drop of water will always be more expensive to collect, to treat and to deliver. So, PUB is always looking for new ways of doing things, for new innovations that will let us produce life-giving, wealth-producing water cheaper and in an easier way. We are crystal clear about achieving three outcomes for water sector innovation: (1) increase water resources; (2) lower cost of production; and (3) improve quality and security.

As you peruse this seventh edition of *Innovation in Water | Singapore*, you will find that every investigation and research study described herein aims to do just this. At the time of publication, the R&D projects count stands at 504, and are collectively valued at almost S\$420 million. This is an impressive tally indeed!

Anaerobic ammonium oxidation, ANAMMOX for short, promises to dramatically reduce the energy take for ridding used water of nitrogen. Inside, learn more about PUB's on-going collaborations with both Meiden Singapore and Nanyang Technological University, as we press onwards to make ANAMMOX technology deployable for municipal used water treatment in tropical conditions.

In this issue, we are pleased to profile the Orange County Water District (OCWD) of California, USA. OCWD is the winner of the Lee Kuan Yew Water Prize in 2014 and an outstanding water authority. OCWD manages a vast groundwater basin that supplies water to 19 municipal and special water districts, and serves more than 2.4

million Orange County residents: work that is even more critical now because of the severe and prolonged drought in California. OCWD leads the way in water reuse. Its Groundwater Replenishment System produces high-quality purified reclaimed water for year round groundwater recharge.

Closer to home, the spotlight falls on the reverse osmosis pilot skid presently installed at Bedok NEWater Factory. This setup allows for pilot tests on a full range of membranes, anti-scalants and chemicals deployment, and is invaluable in helping PUB optimise our plant and production operations.

As midyear approaches, we look forward to the *SIWW Technology and Innovation Summit* in Singapore, 16 and 17 June 2015. Inspired by the success of Singapore International Water Week (SIWW) 2014, and while waiting for SIWW 2016 to come around, we will convene a select group of experts and practice leaders in water management here in Singapore this June.

Our hope is that this group, through guided conversations, will help to illuminate the way forward in terms of the next wave of innovation in water and wastewater management. The *Singapore Summit* will pay specific attention to the municipal and industrial water sectors. Our objectives, after making the case for change, are no less to identify the key technological areas for urgent focus, and to suggest the best ways to bring innovative solutions to market.

As always, I hope you will find this issue to be instructive and informative, and maybe even inspirational. Happy reading!

NG JOO HEE
Chief Executive,
PUB, Singapore's National Water Agency
Executive Director, Environment & Water Industry Programme Office



Harnessing innovation for a water-secure future

Singapore's efforts to ensure water sustainability has seen the country invest in research and technology in a big way, leading to the application of some of the world's most advanced technologies. Playing a key role in this is PUB, Singapore's national water agency. Together with other government agencies, academia and industry partners, PUB's research and development (R&D) activities has positioned Singapore as a global leader in water management and innovation, and helped secure a sustainable water future for its people.

Water is the elixir of life. As a precious resource, water sustains human lives, nourishes the environment, and supports daily livelihood and economic activities. Yet in today's world, more than 750 million people around the world do not have access to safe drinking water and another 2 billion remain without access to basic sanitation.

Remarkably, Singapore, a small city-state with limited natural resources, has succeeded in providing clean drinking water and modern sanitation to its population of over 5 million people. By leveraging excellent water management strategies, a comprehensive R&D programme, and a willingness to adopt innovative new technologies, Singapore has turned a strategic weakness into a source of thought leadership and competitive advantage.

Meeting Singapore's water needs

Singapore's current water demand stands at about 400 million gallons a day, or a volume equivalent to 720 Olympic-sized swimming pools. By 2060, this figure is expected to double. Water from local catchments, imported water, NEWater and desalinated water make up Singapore's water supply known as the Four National Taps. Coupled with an integrative approach towards harnessing new ideas and technology through strategic initiatives and research partnerships, this ensures that Singapore continues to meet its water needs.

NEWater is perhaps the most well-known product of Singapore's pursuit of water sustainability. First introduced in 2003, NEWater is produced by further purifying treated used water with advanced



membrane technologies. It is ultra-clean and safe to drink, having passed more than 130,000 scientific tests, and exceeds the World Health Organisation's drinking water quality standards. NEWater can currently meet 30% of Singapore's water needs, and there are plans to more than triple this capacity to meet up to 55% of future water demand by 2060.

To achieve this goal, Singapore is upgrading its used water management infrastructure through the Deep Tunnel Sewerage System (DTSS) to ensure that all used water is collected for treatment and available for reuse. Under Phase One of the DTSS that was completed in 2008, used water from the northern and eastern parts of Singapore are collected and transported by gravity through a deep tunnel sewer to a centralised water reclamation plant in Changi for treatment. The treated used water is then further purified into NEWater. Phase Two of the DTSS will extend the system to cover the western part of Singapore. It is currently in the design stage and is scheduled to be completed by 2024.

In addition, desalination was introduced in 2005 with the opening of the nation's first seawater desalination plant. This was followed by a second and larger desalination plant in September 2013. Together, both desalination plants are able to supply 100 million gallons of desalinated water daily and can meet up to 25% of Singapore's water needs. To further enhance the resilience Singapore's water supply, Singapore has announced plans to build a third desalination plant.

Leveraging on R&D to prepare for the future

As the national water agency, PUB leads the way in water-related R&D in Singapore through the Environment and Water Industry Programme Office (EWI), an inter-agency body that includes the Economic Development Board, International Enterprise Singapore, and SPRING Singapore. EWI, together with partners from academic institutions as well as industries, spearheads the growth of the environment and water technology industry by focusing on a three-pronged strategy of cluster development, internationalisation and capability development. Capability development, in particular, focuses on building up Singapore's R&D and technology base, and developing the necessary talent and manpower to meet the needs of the sector.

One of the main initiatives under the capability development pillar is the Environment and Water Research Programme which aims to accelerate the process of transforming ideas into innovative applications that can eventually be commercialised. Besides facilitating product development, EWI offers financial incentives

to encourage the early adoption of new technology by end-users, and test-bedding opportunities at PUB's facilities. To support these schemes, Singapore's National Research Foundation has committed S\$470 million towards the programme since 2006. EWI also focuses on grooming the next generation of research and professional leaders to meet the rapidly growing needs of the sector through manpower development schemes such as offering PhD Scholarships.

Arising from these initiatives, Singapore is now home to a vibrant water R&D eco-system with more than 180 local and international water companies and 26 research institutions spanning the water value chain. Through PUB, Singapore has also established strong R&D links with prestigious water research associations and organisations around the world.

Fostering R&D partnerships

PUB's commitment towards fostering research partnerships with local and international research organisations and technology solution providers has resulted in a large number of collaborative R&D projects over the years. These projects focus on PUB's six core areas of interest — Intelligent Watershed Management, Membrane Technology, Network Management, Water Treatment, Used Water Treatment, and Water Quality and Security — and give the agency the opportunity to tap on proven applied technologies to improve its operations. Singapore's continual research efforts to improve water treatment and water reuse processes aim to lower treatment and production costs, and increase Singapore's water resources to ensure that the nation's future water needs will be met.

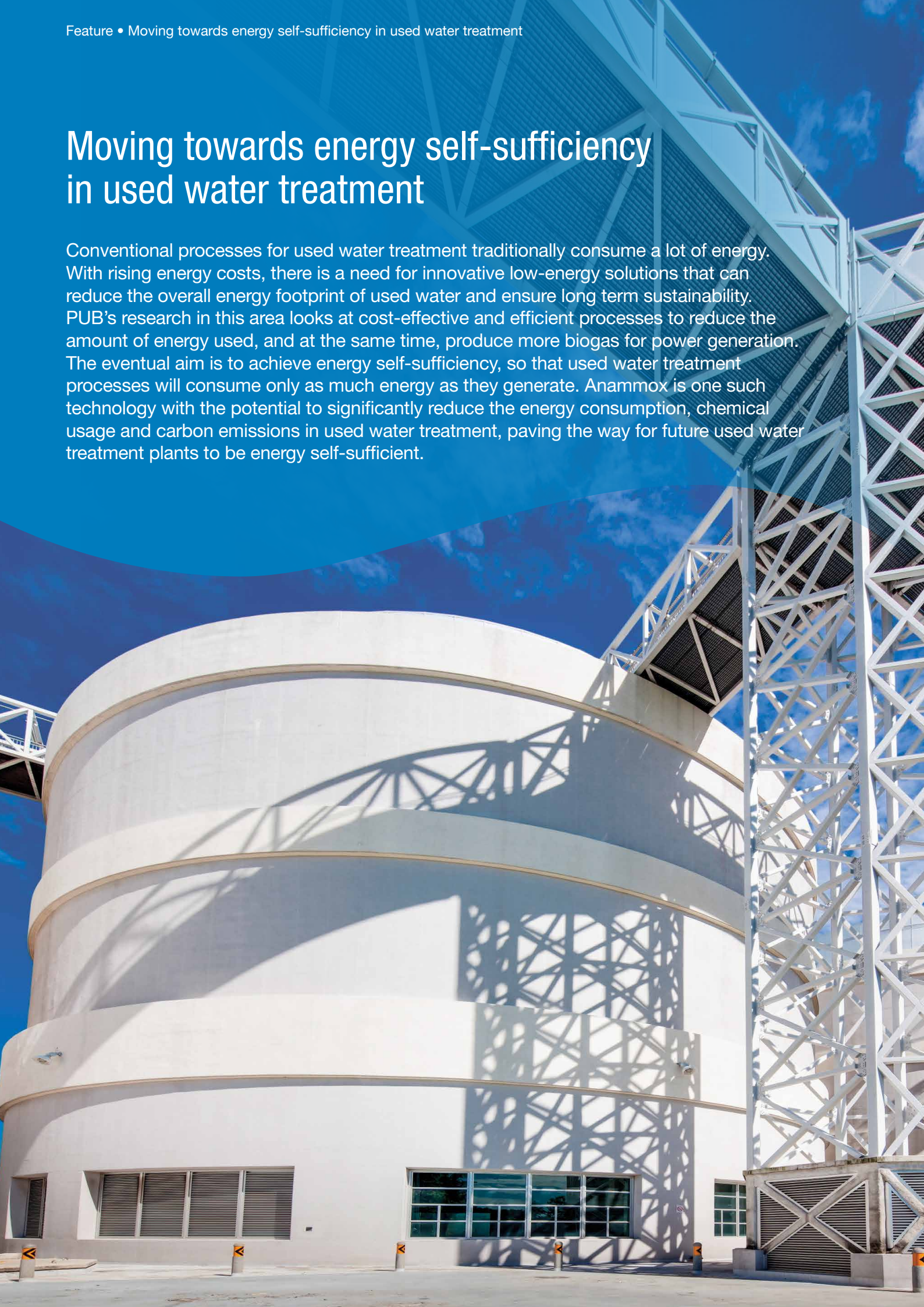
To encourage more research partnerships, PUB has made its water infrastructure, which includes waterworks, reclamation plants, NEWater factories, reservoirs and stormwater canals, and even water pipes, available for test-bedding of new and promising technologies. The opportunity to conduct on-site testing under actual conditions helps to foster the growth and development of emerging technologies, and is a big attraction for organisations looking to develop technologies that can be commercialised. PUB's collaborative strategy not only allows the costs of R&D to be shared, but also reduces the risks for the partnering organisations.

A promising water-secure future

Singapore's unrelenting pursuit of technological innovation to overcome its water challenges has transformed the country into a global leader in water management and technology. The hive of water-related R&D activities and the impressive array of research talent working on its shores make Singapore a global hydrohub. As Singapore continues to push the frontiers of research and innovation, its vision of a water-secure future looks to be well within reach.

Moving towards energy self-sufficiency in used water treatment

Conventional processes for used water treatment traditionally consume a lot of energy. With rising energy costs, there is a need for innovative low-energy solutions that can reduce the overall energy footprint of used water and ensure long term sustainability. PUB's research in this area looks at cost-effective and efficient processes to reduce the amount of energy used, and at the same time, produce more biogas for power generation. The eventual aim is to achieve energy self-sufficiency, so that used water treatment processes will consume only as much energy as they generate. Anammox is one such technology with the potential to significantly reduce the energy consumption, chemical usage and carbon emissions in used water treatment, paving the way for future used water treatment plants to be energy self-sufficient.



Conventional used water treatment is an energy-intensive process. This is largely due to the need for aeration to achieve effective removal of organic carbon and nutrients from the water. In many used water treatment plants around the world, energy costs are estimated to account for as much as 30–40% of total operation and maintenance costs. PUB actively seeks to lower its energy footprint across its used water treatment processes, taking a keen interest in proven technologies that require less energy to treat used water.

One such technology is anaerobic ammonium oxidation, or Anammox in short.

The Anammox and deammonification process

An innovative biological process that converts ammonium and nitrite in used water to harmless nitrogen gas under anaerobic conditions, Anammox was first discovered in the late 1990s by a research group led by Professor Mark van Loosdrecht, 2012 Lee Kuan Yew Water Prize Laureate, at the Delft University of Technology.

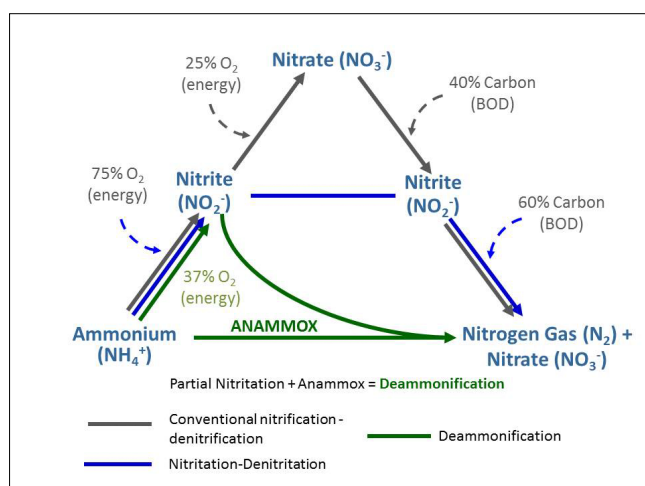


Fig. 1: The deammonification process comprising partial nitritation and Anammox

It is usually coupled with nitritation in a two-step process known as deammonification (Fig. 1). In the first step, nitritation, half of the ammonium in used water is oxidised to nitrite by ammonia oxidising bacteria (AOB). In the second step, the remaining ammonium and the nitrite that has been formed are then converted to nitrogen gas by the Anammox bacteria in the Anammox process. Essential in this engineering is promoting the growth of AOB and Anammox bacteria over that of the nitrite oxidising bacteria, to drive the process in favour of the deammonification process.

Anammox has several advantages over the conventional nitrification/denitrification process in used water treatment. Firstly, the Anammox process itself does not require energy-intensive aeration because the Anammox bacteria convert ammonium and nitrite directly to nitrogen gas anaerobically, short-circuiting the traditional nitrogen removal process. This reduces the overall oxygen demand in deammonification because only part of the ammonium is oxidized to nitrite instead of nitrate, lowering the energy consumption needed for aeration.

In addition, the removal of the remaining ammonium and nitrite through the Anammox process eliminates the need for an organic carbon source. Traditionally, methanol dosing is carried out to augment the organic carbon present in used water for the removal of nitrate and nitrite. With the Anammox process, there is no longer a need for the dosing of methanol thus saving costs. Furthermore, the organic carbon present in used water can now be channelled to digesters to produce biogas for power generation. This results in lower treatment costs and a reduction in carbon dioxide emission by more than 90%.

The Anammox bacteria also easily forms stable self-aggregated granules — compact Anammox systems with high biomass concentrations can thus be reliably operated. The Anammox process produces a relatively smaller amount of excess sludge compared to the conventional nitrification/denitrification process too.

Side-stream deammonification of dewatering centrate in Singapore

In general, deammonification can be applied to treat side-stream used water flows with high-ammonia content or main-stream used water flows with lower-ammonia content. Examples of side-stream ammonia-rich used water include the reject streams from membranes, supernatant liquid from anaerobic digesters (ADs), and the centrate from sewage sludge dewatering processes which typically contain high concentrations of ammonia. Main-stream low-ammonia used water, on the other hand, derives from municipal used water streams.

To date, large-scale applications of side-stream deammonification reactors have been reported in Europe, America and Asia. In Singapore, a research project was undertaken in 2012 to investigate the application of side-stream deammonification in the treatment of dewatering centrate (DC) in water reclamation plants.

The DC, which is the liquid extracted by the dewatering centrifuge from the supernatant of the anaerobic sludge digester, has high ammonia concentration. As the DC is normally returned to the head works of the water reclamation plant, the high ammonia concentration of the DC affects the treatment conditions of the main-stream used water. The removal of ammonia via side-stream deammonification saves aeration energy and contributes towards managing the ammoniacal-nitrogen ($\text{NH}_3\text{-N}$) load in the main-stream used water for NEWater production.



Fig. 2: DEMON® pilot plant at Changi Water Reclamation Plant (WRP)

DEamMONnification, or DEMON[®], is a patented Anammox process used to remove nitrogen from used water with high ammonia concentrations (more than 200 milligrams per litre). It involves treating the DC by the Anammox process in a sequential batch reactor (SBR) to remove the ammonia from the stream. To retain the Anammox bacteria in the SBR, the reactor sludge is passed through a cyclone to separate heavier Anammox bacteria granules from other sludge, which is then returned back to the SBR.

In a collaborative effort between Meiden Singapore, ARAconsult and PUB, a pilot-scale plant was constructed at Changi Water Reclamation Plant (WRP) (Fig. 2) to evaluate the applicability and suitability of the DEMON[®] process in removing ammonia in the side-stream DC under tropical climate conditions.

At the end of the eight-month pilot trial, the results verified that the DEMON[®] process was able to treat the side-stream DC at a target nitrogen loading rate of 0.7 kilogram-nitrogen per cubic metre per day (kg-N/m³/day) with a nitrogen removal efficiency of 80% and power consumption of less than 1.2 kilowatt-hour (kWh) per kg-N removed. The research also found that in the event where there is high chemical oxygen demand (COD) in the DC, the DEMON[®] treatment process can be adapted to address these conditions by adjusting operational parameters such as aeration and sludge removal rate from the cyclone.

Following the success of the pilot trial at Changi WRP, the pilot plant was moved to PUB's Integrated Validation Plant at Ulu Pandan WRP to test the feasibility of applying side-stream deammonification at PUB's future Tuas WRP.

Pilot study on main-stream deammonification

Unlike side-stream deammonification, deammonification of main-stream municipal used water is still largely confined to laboratory-scale and pilot-scale studies.

One reason is because the low ammonia concentration (and consequently, low nitrogen concentration) in the feedwater impedes the growth of Anammox bacteria and makes achieving a stable retention of the Anammox bacteria challenging. This lack of growth and accumulation of Anammox bacteria, in turn, affects the stability of the Anammox process. In order for the Anammox process to work, the COD/N ratio must be reduced significantly.

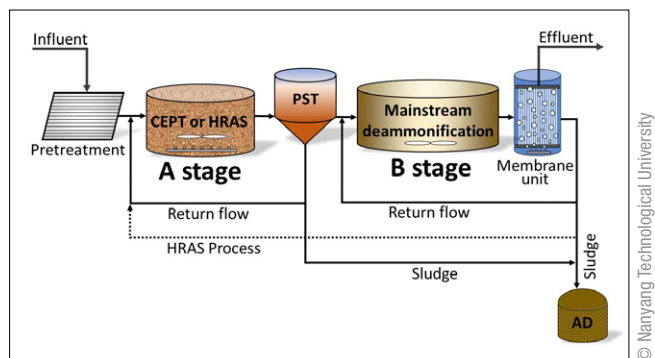


Fig. 3: Process configuration of the two-stage main-stream deammonification

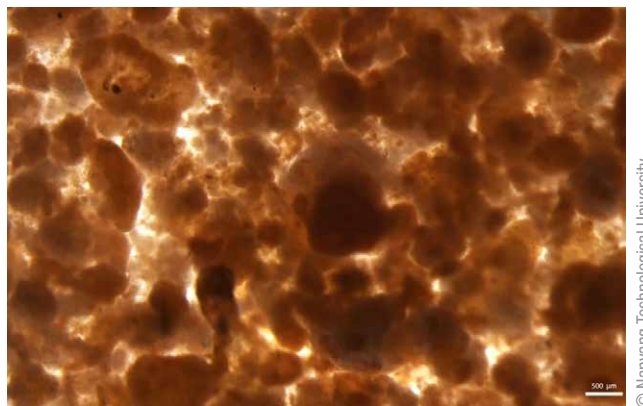


Fig. 4: Anammox bacteria in a laboratory-scale enriched culture

To develop a better understanding of main-stream deammonification in Singapore's tropical climate, researchers from Nanyang Technological University (NTU), led by Liu Yu and Zhou Yan, are currently collaborating with PUB to construct a pilot plant at Changi WRP, with a treatment capacity of 30 cubic meters per day.

A two-stage process configuration was designed for the pilot plant (Fig. 3), with an "A-stage" to reduce COD of the influent and a "B-stage" to remove nutrient compounds. In the A-stage, a carbon capture unit, using either chemical enhanced primary treatment (CEPT) or high rate activated sludge (HRAS), will first remove organic carbon from used water and channel it to an AD for biogas production. After passing through the primary sedimentation tank (PST), the A-stage effluent will have a relatively low COD/N ratio. This effluent will then be treated in the B-stage using main-stream deammonification, which is designed for the selection and retention of AOB and Anammox bacteria, before passing through a membrane separation unit.

The findings of the pilot will be supplemented with parallel laboratory-scale studies to address the interactions among key microbial groups involved in various nitrogen removal pathways (Fig. 4). The NTU team believes that the results of the pilot plant and laboratory studies will allow the team to optimise the operating conditions and eventually achieve the long-term stable performance of the main-stream deammonification system.

Going forward, PUB will continue to scale-up its research efforts to study Anammox and deammonification as viable energy-saving technology alternatives for nitrogen removal in used water treatment. Already, PUB's ongoing research efforts has gained international recognition, with the International Water Association naming PUB's joint research work with AECOM, DC Water, Hampton Roads Sanitation District and Strass Wastewater Treatment Plant on "Unlocking the Mysteries of Mainstream Deammonification – A Paradigm Shift for the Wastewater Industry" a global honour award winner at the 2014 Project Innovation Awards. These efforts could eventually pave the way for the implementation of a full-scale reactor for main-stream deammonification in the near future.

People in Water Research

Orange County Water District



Michael R. Markus, General Manager of Orange County Water District

Orange County Water District (OCWD) was awarded the 2014 Lee Kuan Yew Water Prize for its pioneering work in groundwater management and water reclamation using advanced water reuse technologies, and achievements in public policy and community outreach that have advanced public acceptance of water reuse. Formed in 1933, OCWD manages the large groundwater basin that underlies both north and central Orange County, and provides 70 percent of the reliable, high-quality groundwater to 19 municipal and special water districts, serving 2.4 million customers in north and central Orange County, California, USA.

A culture of innovation through research and development

OCWD has studied, developed and operated some of the world's largest and first-of-its-kind projects. These projects provided the impetus to research a variety of technologies with manufacturers from the water industry, and establish industry standards for water reuse, water quality and groundwater management.

One of these projects, Water Factory 21 (WF-21), began operations in 1976 as a solution to protect the Orange County Groundwater Basin from seawater intrusion. It was the first facility in the world to successfully demonstrate that potable-grade quality recycled water could be reliably produced from treated used water effluent through an advanced water purification system relying on reverse osmosis and granular activated carbon (Fig. 1). Since then, based on continual research and demonstration efforts by OCWD, a three-stage advanced treatment process of microfiltration, reverse osmosis and ultraviolet/hydrogen peroxide has been established as the standard for potable water reuse in the industry. Not resting on its laurels, OCWD undertook research initiatives such as looking into membrane fouling mitigation measures and studies of advanced oxidation processes to further optimise and improve its treatment processes.



Fig. 1: Water Factory 21, the pioneering water recycling facility

With WF-21, OCWD established itself as the pioneer in water reuse and groundwater management. It helped pave the way for many international water reuse projects and ultimately the Groundwater Replenishment System (GWRS) that is in use today (Fig. 2). The GWRS is the world's largest water reuse facility for purifying wastewater into high-quality drinking water for injection and percolation into the groundwater basin.

Besides the GWRS, OCWD also operates an internationally acclaimed managed aquifer recharge system to capture surface water, stormwater, imported water, dry weather runoff and recycled water to replenish the groundwater basin it manages. To more efficiently capture and recharge water and increase the drought resilience of the region, OCWD looks to research. For example, OCWD conducts field-scale pilot evaluations

of passive riverbed filtration and cloth filtration technologies to remove fine sediments from local surface water used for aquifer replenishment. A reduced sediment load would lead to reduced physical clogging of recharge basins and decrease the frequency of basin cleanings, which is especially important for maximizing groundwater recharge during storm events. Other related ongoing research includes investigations of basin cleaning methodologies, sediment transport, and studies on the impact of aquifer recharge with high purity water on its water quality.



Fig. 2: Orange County's Groundwater Replenishment System Facility

PUB's long-term partnership with OCWD

The OCWD's work in advancing water reuse research has had a global impact, in particular, for PUB and Singapore.

In the days of WF-21, PUB sent a team to learn about its water reuse treatment process and OCWD's research. Later, PUB continued to engage OCWD on key water reuse issues, establishing and maintaining a collaborative relationship to share knowledge, experience and expertise.

Since then, PUB's partnership with OCWD has grown. An OCWD executive staff member currently sits on PUB's External Audit Panel to assist and advise PUB on the management of water resources in Singapore. A staff exchange programme has also been implemented to enhance learning opportunities. More recently, OCWD's chief hydrogeologist was appointed by PUB to be part of a panel to evaluate the potential for groundwater development in Singapore.

A commitment to high-quality and reliable water supply

To this day, water research continues to help OCWD fulfill its mission to provide an adequate, high-quality and reliable water supply to local water retailers at the lowest reasonable cost in an environmentally responsible manner. OCWD is committed to advancing water research on issues that improve its operations and it will continue to explore the feasibility of projects that increase and protect local water supplies.

Improving NEWater plant operations



For a country with limited natural water resources, Singapore has successfully diversified its water sources through the Four National Taps, which comprise water from local water catchments, imported water, desalinated water and NEWater. NEWater, in particular, is the crown jewel of the Singapore water story and its success has attracted interest from water utilities and governments worldwide.

Introduced in 2003, NEWater is reclaimed used water that has undergone stringent purification and treatment processes using advanced membrane (microfiltration or ultrafiltration and reverse osmosis (RO)) and ultraviolet technologies. It is supplied mainly to

industries for non-domestic uses, and used to top up the reservoirs during the dry months. This is known as planned indirect potable use.

To produce NEWater, clarified secondary effluent from the used water treatment process is introduced as feedwater in the NEWater factory. This secondary effluent is first micro-screened, before passing through microfiltration or ultrafiltration to remove fine solids and particles, and then further purified with RO to remove bacteria, viruses and most dissolved salts. The RO permeate is finally disinfected by ultraviolet radiation, producing a high-grade, ultra-clean reclaimed water end product that is NEWater.



Pilot RO skid to test and optimise NEWater processes

Today, Singapore has four NEWater factories that are capable of meeting up to 30% of its water needs. A fifth NEWater plant is expected to commence operations by 2016, and there are plans to expand NEWater capacity to meet up to 55% of future water demand by 2060. It is therefore essential for PUB to continue to optimise the performance of its NEWater operations through research and development.

To ensure that research efforts can be conducted without affecting actual plant operations, PUB set up a parallel RO pilot skid at the Bedok NEWater Factory (BNF) (Fig. 1) for the offline testing of commercial RO membranes, antiscalants and other chemicals. Installed in a 20-foot container, the pilot skid consists of two parallel RO systems, each with a capacity of 333 cubic metres per day (Fig. 2). The pilot skid is portable with a flexible piping system that can be dismantled easily, allowing for various plug and play configurations. It is equipped with

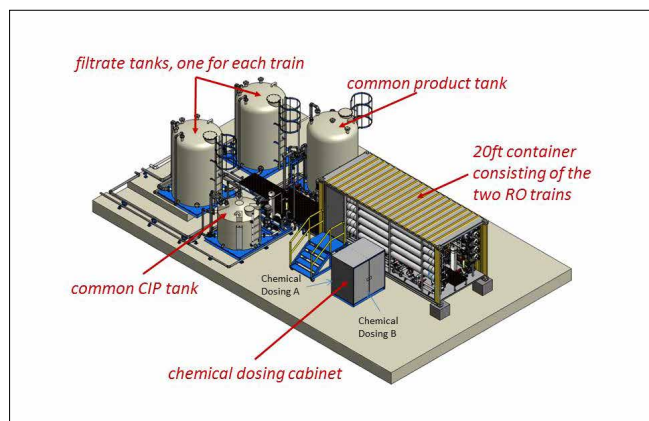


Fig. 1: Schematic of the RO pilot skid at Bedok NEWater Factory

the required process control and monitoring instrumentation, including online sensors, to measure pH, conductivity, flow, temperature, and pressure at all stages of the NEWater production process for performance monitoring and verification.

In addition, the pilot plant consists of individual chemical dosing systems which allow for dosing of various chemicals such as antiscalant and biocide for each RO train. These chemicals are stored in a mobile chemical cabinet located beside the container, alongside the Clean-In-Place (CIP) membrane cleaning system and recirculation tank. This comes in handy as the CIP system allows the membranes to be cleaned using a variety of chemicals, including acids and bases. Once the cleaning is completed, the RO membranes are flushed immediately with permeate water to remove any residual surfactants.

Parallel testing and comparison of different membranes

To assess the performance of different membranes, both RO trains in the skid are operated simultaneously to conduct parallel testing of different commercial membranes using similar feedwater and operating conditions to that of the BNF.

A baseline of basic parameters such as energy consumption, pressure, flow, water quality parameters and frequency of cleaning was first established for both sets of membranes. Following that, a series of studies was conducted to compare membrane performance. These tests include a comparison of the efficiency and required dosage of different antiscalants in preventing scaling on the membranes, the effects of varying fluoride levels on the scaling potential of the membranes, the efficiency of the chemical cleaning, and the effect of varying the antiscalant dosing points on scaling and the efficiency and consumption of the antiscalant.

Optimisation of RO system performance in NEWater production

Results from the studies conducted at the pilot skid will allow PUB's engineers to optimise the RO system performance and potentially increase RO recovery rates. Such optimisation will also reduce the chemical and energy consumption required in the plant, which in turn reduces the overall operational cost for NEWater production. In addition, it allows PUB to compare and validate the study results against performance projections given by the membrane manufacturers and chemical suppliers, enabling the agency to make better-informed decisions on the selection of membranes and chemicals for plant operations.

PUB has commenced testing of several commercial membranes and chemicals using this pilot skid. Membrane manufacturers have also benefited from the testing as it allows them to understand the performance and efficiency of their newly developed variants in actual feedwater and operating conditions. Similarly, chemical suppliers are able to optimise the dosage levels of chemicals required in actual feedwater and demonstrate the performance of their product before they participate in commercial tenders.



Fig. 2: The two parallel RO trains in the pilot skid, complete with process control and instrumentation monitoring

As PUB continues to lay the groundwork to augment NEWater as a sustainable source of water for the future, PUB welcomes companies to test their technologies and products which can improve its NEWater operations at this facility. For enquiries, please visit www.pubwaterresearch.com.sg/ContactUs.aspx.



INTELLIGENT WATERSHED MANAGEMENT

The Intelligent Watershed Management programme aims to leverage developments in instrumentation, controls and innovative information technology solutions as modelling tools for hydraulics and hydrology research. These enhance Singapore's capability in managing its water resources. Using high-level simulations, water researchers in Singapore can forecast future events and plan efficient countermeasures.



Polishing stormwater runoff through bioretention systems

Implementation of bioretention systems such as rain gardens can help in the removal of total suspended solids, total nitrogen and total phosphorus in stormwater runoff



Fig. 1: Pilot-scale bioretention unit to assess the impact of filter media depth and plants on effluent water quality



Fig. 2: Full-scale demonstration of a rain garden to improve runoff water quality

Bioretention systems such as rain gardens are increasingly being implemented to provide detention and effective treatment of urban stormwater runoff. These systems naturally remove total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP) in stormwater runoff, improving the quality of stormwater that flows to the reservoirs. A National University of Singapore research team led by Jiangyong Hu, together with PUB, undertook a study to develop a novel modular soak-away bioretention system with engineered soil that would be effective for use in Singapore and other tropical areas.

The type of filter media used in bioretention systems plays an important role in the treatment of stormwater runoff. As the physicochemical properties of commercially available planting soil and sand vary considerably, engineered soil with a prescribed composition and lesser sandy material offers advantages such as ease of preparation and lower cost.

To establish the optimum engineered soil mix, Hu and her colleagues conducted column tests on different soil mixes. Soil amendments such as compost, coconut fibre and water treatment residues (WTR) were incorporated in various proportions and homogeneously mixed with sand. “Results showed that an engineered soil mix of sand, WTR and compost was able to achieve the best removal of TSS, TN and TP,” Hu shares.

Using the engineered soil mix as filter media, Hu’s team constructed a bioretention unit as a mock-up rain garden to assess how the depth of filter media and plants impacted effluent water quality (Fig. 1). Rainfall events were simulated using synthetic stormwater with pollutant and hydrologic characteristics commonly observed in Singapore’s rainfall and urban runoff. The results showed a 97% removal of TSS and TP across different filter depths, while the removal of TN increased with filter depth and operational time.

Following the mock-up study, a full-scale demonstration soak-away rain garden was implemented in a local college to validate its treatment performance (Fig. 2). Sized to capture runoff from the college premises, the rain garden used the same engineered soil mix and locally available plant species. Rainfall intensity, as well as influent and effluent water quality, were monitored over a continuous twelve-month period. Results at the end of the period indicated a noticeable reduction in effluent TN concentrations over time, although there was no distinct trend in TSS and TP removal due to their low influent concentrations. The treated effluent was able to meet the stormwater treatment objectives stated in PUB’s Active, Beautiful, Clean Waters (ABC Waters) Design Guidelines.

The successful demonstration of the rain garden and the lessons learnt will be valuable as more bioretention systems can be implemented in future under PUB’s ABC Waters Programme and in projects by other agencies and private developers.

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Using SWAN to monitor water quality in reservoirs

New generation Smart Water Assessment Network has spatial and temporal water quality monitoring capabilities that can help to monitor reservoir water quality



Fig. 1: NUSwan robots performing water quality profiling in Pandan Reservoir

Freshwater reservoirs are complex environments that are highly dynamic over time and space. The water quality of the reservoir can be affected by factors such as increasing urbanisation, recreation and other human activities in the catchments and reservoirs. At present, water quality monitoring is typically conducted using fixed online stations which provide limited coverage, by taking a boat to fixed locations to collect grab samples, or by taking manual in-situ measurements, which are tedious and time-consuming.

To address this challenge, a team at the National University of Singapore led by Teong Beng Koay is developing a smart robotic platform that allows both spatial and temporal monitoring of water quality in Singapore's freshwater reservoirs. Named NUSwan, the robot is designed to look like a white swan and traverse unmanned across the reservoir surface to perform water quality profiling at locations of interest (Fig. 1).

The NUSwan is designed to autonomously plan an energy-efficient route to the selected monitoring points. The system also minimises operation logistics by removing the need for a support vessel as the robot autonomously returns to a predefined shore-based service station for regular maintenance and charging. The data collected on-board the robot will be streamed in real-time to a command centre for efficient dissemination to the operators, and the sampling behaviours can be altered by the operators remotely based on the observed data.

A typical NUSwan operation would involve deploying multiple NUSwan robots to simultaneously and collaboratively sample an area of interest. This operational strategy makes it possible to detect gradients across a plume, allowing for a better appreciation of the distribution of nutrients in the area (Fig. 2). "We hope to generate new insights into our environment with the new interactive sampling capability and improved spatio-temporal sampling resolution," says Koay.

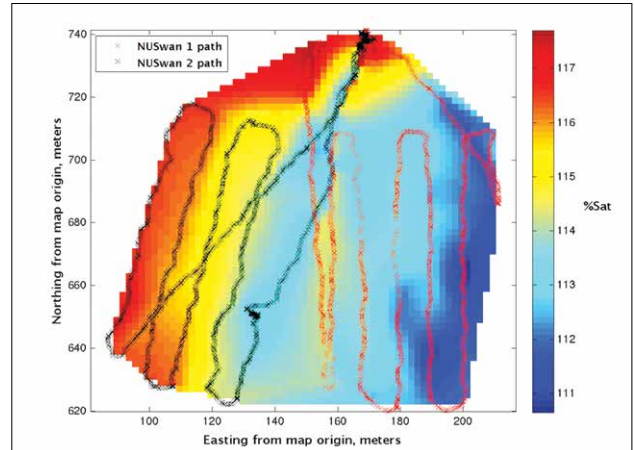


Fig. 2: spatial estimate of dissolved oxygen levels based on readings from NUSwans

Besides operating as a stand-alone system, the NUSwan can also be deployed with other monitoring platforms. For example, when deployed together, NUSwan and underwater robots complement each other in their operations, providing enhanced profiling of both the reservoir surface and the entire reservoir depth for better understanding of the environment. The NUSwan can also be deployed together with fixed buoy monitoring systems to significantly expand the spatial coverage of monitoring.

The NUSwan currently carries standard, commercially available sensors for measuring parameters such as Chlorophyll-a, dissolved oxygen, turbidity, and blue-green algae, and can be extended to include new sensors. Combined with real data delivery, the NUSwan potentially serves a wide range of applications, such as water body surveillance, autonomous spot water sampling, and pollutant tracking, and has the potential to be integrated as part of early warning and decision support systems.

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Water in drains gets a clean-up

Bioremediation wetlands in drains and canals can help to clean base water flows



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Fig. 1: Flume experiments were tested with various plant species to analyse their impact on the effectiveness of the wetland

Singapore’s catchment areas are largely characterised by impervious surfaces such as asphalt and concrete. When it rains, runoff flows quickly over these surfaces, often carrying pollutants from these catchments into our drains and canals. While this rainwater is an important source of freshwater supply, the highly urbanised environment also makes it prone to point and diffuse sources of pollution.

Sparked by an idea arising from public engagement under the Active, Beautiful, Clean Waters (ABC Waters) Programme, PUB embarked on a study with Sheela Reuben, Seng Keat Ooi and colleagues from the National University of Singapore, as well as scientists from Deltares and the Delft University of Technology in the Netherlands, to explore the design of an in-stream wetland (a bioremediation wetland built within an existing drainage channel) that can potentially clean the base water flow in the canal.

Using the Zhenghua Road Outlet Drain next to Pang Sua Pond as a pilot site, Reuben and her team first surveyed the site to establish the baseline water quantity and quality parameters. The data was then used in flume experiments where different substrate layers and plant species were tested in scaled-down models of the in-stream wetland to determine its water residence time and bioremediation efficiency (Fig. 1).

“Approximately 75% of suspended sediments were removed,” shares Reuben. “However, the residence time was too short for substantial nutrient removal in the short term.” Reuben’s team also discovered that based on vegetation models, plant height, and not planting density, was the determining factor for plant stability in the proposed wetland.

To assess if the in-stream wetland would lead to an increased flood risk, data from three high flow rain events in the study site was fed into simulation models. Flume experiments were also carried out to determine possible erosion of the wetland’s sediment top layer, and the impact of lateral mixing in a partially vegetated flow on upstream flood risk.

“We found the risk of increased flooding to be negligible at high flow conditions. The model wetland in the flume experiments was also able to survive the conditions similar to that in the field,” says Ooi.

With information gathered from experimentation and modelling, final adjustments were made to the proposed wetland design including, among others, the use of more effective plant species, the placement of a sedimentation pond before the wetland, the selection of specific substrate size to reduce the risk of clogging the substrate (Fig. 2), and the reconfiguration of the wetland to be as hydraulically smooth as possible.



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Fig. 2: Column experiments determine the hydraulic conductivity of the designed wetland

It is foreseen that the first pilot in-stream wetland would be installed in the Zhenghua Road Outlet Drain by early 2016, where it will be monitored to further understand the efficacy of the pilot wetland.

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MEMBRANE TECHNOLOGY

Membrane technology has played a vital role in the development of NEWater in Singapore. Dating back to 1974 when a demonstration plant was set up to study the feasibility of reclaiming used water using physicochemical processes, the technology has since grown and developed. NEWater is now a key pillar of Singapore's water strategy.

Backed by almost 40 years of experience, Singapore's water researchers continue to explore innovative ways of applying and optimising membrane processes for water and used water treatment.

Improving membrane permeability by mimicking nature

Enhancing and validating the performance of aquaporin-based biomimetic membranes for water reuse

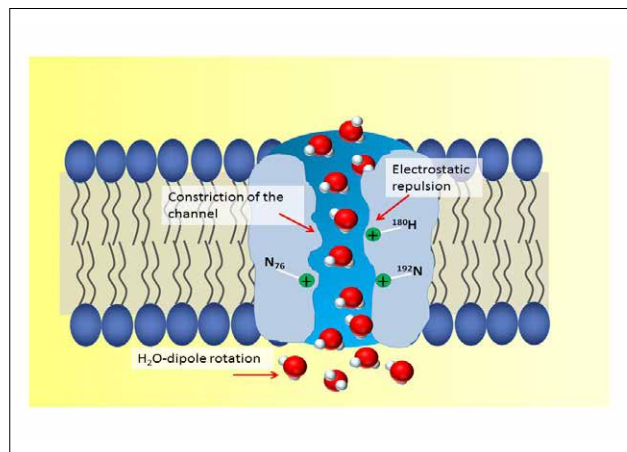


Fig. 1: Schematic depiction of water movement through the narrow selective filter of the aquaporin channel

Nature could well hold the solution to the search for more efficient membranes according to a recent study by researchers from the Singapore Membrane Technology Centre (SMTC) and Nanyang Technological University in collaboration with PUB.

Aquaporins are a group of water channel proteins widely found in mammals, plants and bacteria. Due to their high permeability and specific structure, aquaporins can transport water molecules efficiently at approximately a billion water molecules per second while rejecting other solutes (Fig. 1).

Aquaporin-based biomimetic membranes (ABM) combine this unique characteristic of aquaporins with membrane technology to exhibit much higher water permeability than the conventional reverse osmosis (RO) membranes. The higher permeability of ABM means that a lower operating pressure is required to achieve the same water flux, resulting in improved membrane performance, reduced energy consumption, and lower overall cost.

In the first stage of the project, the team developed a protocol to fabricate ABMs using a method known as interfacial polymerisation (IP), where aquaporins are embedded in the membrane selective layer (Fig. 2). This method increases the water permeability of the membranes, protects the embedded aquaporins from external environments, and helps to reduce the defects of the membrane. By 2012, the SMTC team had successfully fabricated ABMs with a permeability that was approximately 40% higher than that of commercial brackish water RO membranes, and with a higher order of magnitude as compared to seawater RO membranes. Furthermore, the membrane fabrication process developed could be easily scaled up for practical applications.

Following this initial success, the team proceeded to further improve the membrane properties and examine the long-term performance of the ABM for water reuse. Parallel experiments were conducted

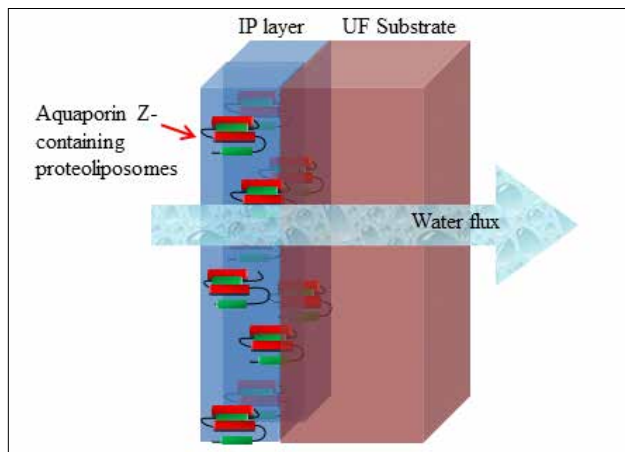


Fig. 2: Conceptual drawing of aquaporin-based biomimetic membranes (ABM)

by passing synthetic and real NEWater RO feedwater through the membranes under an applied pressure of 10 bars continuously for two weeks.

The result showed that the ABM produced a relatively stable water flux when synthetic RO feed solution was used. The flux achieved by the ABM was nearly double that of what was achieved by the control membrane without aquaporins embedded, with no significant difference in ion rejection observed. When the test was switched to real NEWater RO feedwater, fouling was detected on both the ABM and control membranes. Despite the fouling, the ABM still exhibited much higher water permeability, with only half the applied pressure required to achieve the same water flux as the control membrane.

Moving forward, the team aims to further optimise the design, fabrication, and operation of ABMs, particularly in a hollow fibre configuration, and eventually pave the way for biomimetic aquaporin membranes to be used in large-scale applications.

Researchers and affiliation

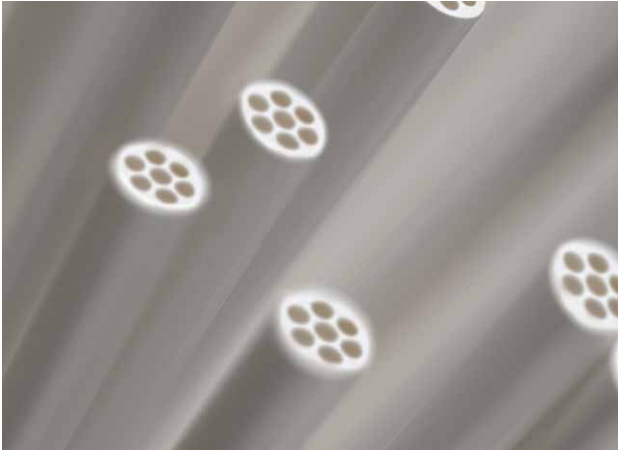
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Using chemistry to improve membrane performance

Pilot study demonstrates flux enhancement of chemically-modified ultrafiltration membrane materials



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Fig. 1: The patented Multibore® membrane technology combines seven individual capillaries in a highly robust fibre — an arrangement that significantly increases the membrane's stability and eliminates the risk of fibre breakage

Ultrafiltration (UF) is increasingly being applied as a pre-treatment process prior to reverse osmosis (RO) in seawater desalination. BASF's global research team in Germany and Singapore recently developed a novel membrane material that exhibits superior anti-fouling properties through polymeric chemistry. The new material allows the membrane to be operated at higher flux, thus lowering capital expenditure and operational costs for water treatment.

Made from BASF's proprietary polymer Ultrason®, the Multibore® UF membranes consist of hollow fibres that each bear seven individual capillaries (Fig. 1). Water flows into these seven channels, and is filtered through tiny pores in the capillary walls. The pores have an inner size of about 20 nanometers — large enough to allow water molecules to pass, but small enough to retain dirt particles, bacteria, and even viruses.

In the development of the new membrane material, the team adopted parallel studies at the laboratory scale, making modifications to the polymer and anti-adhesive additives. The resultant additives were then incorporated in dope polymer solution during membrane fabrication to obtain the new chemically-modified UF fibre membranes.

Prior to long-term piloting tests, the performance of the new membranes was evaluated in the lab through organic fouling testing protocol, where they exhibited a decreased fouling propensity. To further validate the positive findings from the laboratory, the BASF team worked with PUB to test-bed the new membranes in a pilot trial at PUB's R&D facility (Fig. 2). Using the same seawater feed as that of the Tuaspring Desalination Plant, the pilot plant was operated under the same conditions as actual UF operations during the pre-treatment process for seawater desalination.

The new membranes were benchmarked against BASF's standard commercially-available membranes in terms of flux performance and chemical cleaning requirement over a period of six months. The



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Fig. 2: Pilot plant to test the membranes under actual ultrafiltration operational conditions

new membranes could be operated at a high stable flux of up to 130 litres per square metre per hour (LMH), and required only half the normal sodium hypochlorite concentration used for the backwash as compared to the standard membranes. This shows a marked improvement over the standard membranes which would have to be operated at a reduced flux for the same amount of cleaning chemical used. The new membranes were further operated without using sodium hypochlorite for its chemical enhanced backwash to test their limits and confirm their advantages.

The encouraging results of the pilot study suggest that chemistry plays a pivotal role in the overall performance of polymeric UF membranes. The BASF team is currently continuing their research to further validate the improvement of the new membranes with commercial-scale modules in other applications, such as in drinking water production and waste water reuse, and aims to bring this new technology to the marketplace in the near future.

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Recovering water from desalination brine

Looking to reverse-electrodialysis-based seawater desalination technology for higher recovery and reduced capital costs



Fig.1: Setup of a laboratory-scale Reverse Electrodeionization (RED)/driven Reverse Electrodeionization (dRED) stack during the pilot study

The recovery of water from brine generated by seawater desalination may soon become a viable reality if ongoing research by GE Water and Process Technologies proves successful. In collaboration with PUB, Harikrishnan Ramanan and colleagues from GE are investigating the feasibility of adopting Reverse Electrodeionization (RED) and driven Reverse Electrodeionization (dRED) technologies to increase the water recovery rates of existing desalination systems using low salinity effluent from used water reclamation processes as a salt sink.

According to Ramanan, the typical RED/dRED setup involves constructing a stack with cell pairs comprising of alternating cation exchange membranes (CEM) and anion exchange membranes (AEM) separated by alternating concentrated and dilute spacers, where high salinity (e.g. desalination brine) and low salinity (e.g. NEWater brine) water streams are used as feed streams.

During RED, the salinity gradient causes the sodium (Na^+) and chloride (Cl^-) salt ions to spontaneously migrate from the concentrated stream to the diluted stream. As CEM only allows the transport of cations and AEM, the transport of anions, cations (Na^+) will move in one direction and anions (Cl^-) will move in the opposite direction. To increase the transport rate of ions from the concentrated stream to the diluted stream, an external electric potential may be applied; this process is known as dRED. Applying dRED to recover seawater brine can potentially double the capacity of a desalination plant, without the need for additional intake, pre-treatment and outfall capacity, thereby leading to significant cost savings.

In a laboratory-scale study, Ramanan's team constructed a pilot stack comprising of 20 cell pairs (Fig. 1). Various types of ion-exchange membranes (both cation and anion) and different spacer designs were investigated, while different combinations of salt concentrations were tested as the dilute and concentrate streams.

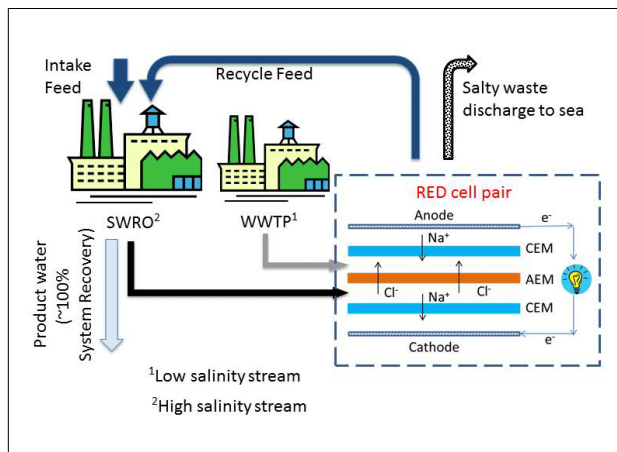


Fig. 2: Schematic diagram of the RED/dRED process for desalination applications

From the experimental results, key output parameters such as open circuit voltage and the resistance per cell pair were determined and used to calculate the maximum power density of the stack.

“We were able to validate that high power densities were attainable with GE’s ion-exchange membranes and spacers in RED mode,” Ramanan says. “At the same time, our membranes also require significantly less power to move the same amount of ions in dRED mode.”

Moving forward, Ramanan and colleagues set up a pilot plant in Tuas in early 2015 to study the processes further by using actual brine streams under realistic scaling and fouling conditions. He believes the pilot operation data coupled with the model development would aid the eventual scale-up and process optimisation of brine recovery in large-scale desalination plants (Fig. 2) using the new RED/dRED technology.

This research is funded by the Singapore National Research Foundation under its Environmental & Water Technologies Strategic Research Programme and administered by the Environment & Water Industry Programme Office (EWI).

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NETWORK MANAGEMENT

Singapore's water strategy focuses on the management of water resources in an integrated manner across all points of the water loop. In the field of network management, a key aim of water research and development in Singapore is to ensure the delivery of high-quality water from the waterworks and NEWater factories to customers while ensuring the collection and reclamation of used water in an effective and efficient manner.

The management and maintenance of Singapore's water networks is therefore a critical function, as well as a responsibility that spurs Singapore's water researchers to greater technological innovation.



Solving the mystery of biofilm growth in pipes

Operation and validation of an in-pipe sensor to monitor biofilm development in water distribution systems

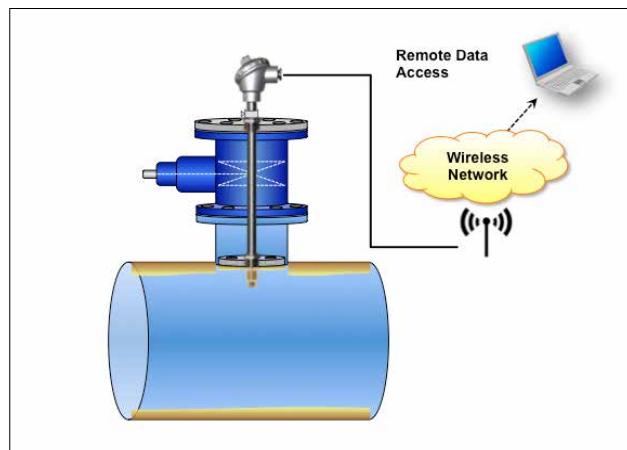


Fig. 1: Installation of an in-pipe biofilm sensor with online monitoring data acquisition within a water pipe

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Fig. 2: Investigating the occurrence of target microbes in biofilms using molecular biological methods

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Biofilms occur universally on submerged surfaces in water supply systems, including storage tanks, distribution networks, consumer taps and showerheads. While biofilms play a beneficial role in some water treatment processes (e.g. slow sand filtration and biological activated carbon), its development in water distribution systems is usually considered undesirable, and is associated with the decay of residual disinfectant, nitrification, and microbiologically-influenced corrosion.

There is limited knowledge of biofilm growth rates within the potable water network, and its relationship with the local hydraulic regime, water age and water quality. In practice, it is difficult to collect biofilm samples as access to pipe surfaces within an operational water distribution system is limited. In a collaborative project with PUB, Andrew Whittle and Masaaki Kitajima from the Massachusetts Institute of Technology and Singapore-MIT Alliance for Research and Technology Centre aim to measure biofilm growth rates using in-pipe sensors as a first step towards the development of strategies for managing the associated water quality issues.

Whittle and Kitajima plan to install wireless in-pipe sensors to measure the electrochemical activity of aquatic biofilms at selected locations within the water distribution system (Fig. 1). These sensors are attached to the ends of steel rods and installed within the distribution pipes via the gate valves. The strength of the electrochemical signal captured by the sensor is proportional to the sensor surface area covered by bacteria, giving a real-time indication of the biofilm growth rate. The online monitoring data (i.e. quantitative measurement of biofilm growth rate) will be transmitted to the team wirelessly.

The performance of the in-pipe biofilm sensors will be evaluated by validating the sensor response with offline biofilm measurements, conducted by sampling biofilms from the bottom surface of coupons attached to the sensor rods. These biofilm samples will

be brought back to the laboratory and subjected to quantification of microbial numbers with culture-based assays and quantitative polymerase chain reaction (q-PCR) (Fig. 2).

According to Whittle, the results of the study will provide insights to how biofilm development is related to factors such as pipe size, material and age, local hydraulic conditions (operating pressures, flow rates, water age), and local chemical environment and water quality (turbidity, oxidation-reduction potential, residual chlorine, microbial numbers).

“This study will allow us to generate more comprehensive and detailed information on biofilms within the potable distribution system, ultimately improving control of the quality of water that is delivered to consumers,” says Whittle.

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Intelligent technologies to reduce water leakage in pipes

Verification of intelligent leak detection technology to manage and reduce water loss from water distribution networks

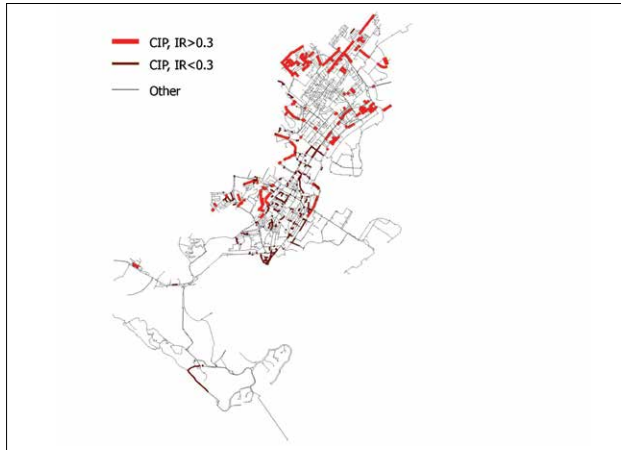


Fig. 1: Leakage risk map of cast iron pipes in the test-bedding zone

Conventional methods such as water audit analysis and leak surveys using acoustic instruments to locate leaks in water distribution networks are often labour-intensive and time-consuming. Water utilities are therefore increasingly turning to “intelligent” leak detection technologies to help them reduce and manage non-revenue water more efficiently.

In collaboration with PUB, Casey Tsui and colleagues from Hitachi have completed a test-bedding project using Hitachi’s leak detection technology which can potentially improve PUB’s leak management capabilities. Utilising asset information from PUB’s Geographic Information System (GIS), sensor measurements in its Supervisory Control and Data Acquisition (SCADA) system, customer consumption data, and recorded operation log, field verification of Hitachi’s technology was carried out in a designated PUB water supply zone.

Using asset information and historical leakage incident data, the team first constructed a leakage risk model on Cast Iron Pipes (CIP) (Fig. 1) as a tool to predict leakage risks from pipe corrosion. Comparing the model against actual incident rates during 2010 to 2012, they found that the constructed risk model matched well qualitatively with the observed data. “This correlation demonstrates the value of the risk model as a tool to help utilities predict pipe leakage and plan their pipe replacement programme,” explains Casey.

The team then divided the test-bedding water supply zone into smaller areas to field-test Hitachi’s methodology for estimating area leakage, defined as the aggregated quantity of leakage in a specified area regardless of the size of individual leaks.

In the field test, various scenarios of area leakage were simulated by discharging water from fire hydrants within each area at different discharge rates (Fig. 2). For each scenario, Casey and his colleagues analysed the pressure sensors for any significant



Fig. 2: Discharge set-up at a fire hydrant for simulating area leakage

changes in pressure. The pressure changes were then correlated with the discharge flow rates to verify that they were caused by the simulated leakage instead of usual variations in local demand.

The team verified that their methodology was able to successfully identify an area leakage at a simulated leakage rate of 180 cubic metres per hour (m³/h), or 3.5% of the average system flow. However, no relevant pressure changes were detected at lower discharge rates.

“The verification result suggests that the technology can be applied to narrow down specific areas with high leakage rates in a water supply zone. This allows the utility to adopt a more targeted approach towards leak management,” explains Casey.

Moving forward, Hitachi intends to market this system proactively in countries where water leakage rates are an issue, in tandem with other offerings as it further accelerates the global development of its water environment solutions business.

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Monitoring cyanide in used water

Test-bedding of an online cyanide analyser for used water applications



Fig. 1: The CL603 online cyanide analyser

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Fig. 2: Sampling tank used in the trial, where samples were drawn out for testing

© Awa Instruments

Cyanide is classified as a hazardous substance in Singapore with an allowable discharge limit of 2 milligrams per litre (mg/L) into public sewers. It is also a known inhibitor of the nitrification process, and its presence in used water can potentially cause severe disruption to downstream biological used water treatment processes.

In a collaboration with PUB, a team from Awa Instruments test-bedded their cyanide analyser CL603 (Fig. 1) for the detection of cyanide in trade effluent. They aimed to assess the reliability of the CL603 analyser in providing real-time continuous monitoring and early detection of cyanide presence in industrial trade effluent.

The project team collaborated with a factory that uses cyanide compounds in its operations. The CL603 analyser was installed at the site, and continuous monitoring was successfully achieved for 10 weeks without operation and maintenance disruption.

The team first carried out a correlation analysis between readings from the CL603 analyser and results from the accredited laboratory test method APHA 4500 CN-N for measuring cyanide. Using standard cyanide calibration solutions of 1–5 parts per million (ppm), the analyser readings and laboratory results were compared. A high correlation factor of 0.99 was obtained, indicating the CL603 analyser was reliable under laboratory conditions and in the absence of interfering substances in the solution samples.

The CL603 analyser was then validated using actual trade effluent samples. Unlike standard cyanide solutions, trade effluent contains many chemicals that can interfere with cyanide ions present in the used water. These can cause lower readings on the online analyser when compared to actual cyanide concentrations and to those obtained using laboratory test methods.

The team took effluent samples from two locations — the factory's used water pre-treatment plant and the manhole serving industrial

clusters — for analysis (Fig. 2). However, as the cyanide concentrations in these samples were below the laboratory test method's minimum detection limit of 0.005 ppm, cyanide was added synthetically to the samples for both the CL603 and for the laboratory test prior to testing to increase the concentrations to between 1–5 ppm. Similar to the earlier correlation analysis, the CL603 readings and laboratory test method results showed good correlation for both effluent samples. This, according to the team, demonstrates the consistency of the CL603 analyser.

The results obtained from this test-bedding project indicate that the CL603 is suitable for online monitoring of cyanide. This can benefit end users such as industries, regulators and even utilities like PUB, in their daily operations.

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USED WATER TREATMENT

Singapore's research in used water treatment focuses on closing the water loop to short-circuit the water cycle. Instead of discharging treated used water into the sea and relying on the natural hydrologic cycle of evaporation, cloud formation and rainfall to recycle the water, Singapore's water scientists intervene to close the water loop by reclaiming used water and distributing it for large-scale non-potable use by industry, as well as for indirect potable use.

To do this, Singapore's water scientists work to develop innovative, cost-effective and efficient processes using technologies for sludge minimisation, biogas utilisation and odour destruction that can achieve high quality effluent.



Treating municipal used water using anaerobic systems

Pilot-scale demonstration of ZeeWeed® anaerobic membrane bioreactor technology to treat used water



Fig. 1: The ZeeWeed® anaerobic membrane bioreactor (AnMBR) pilot

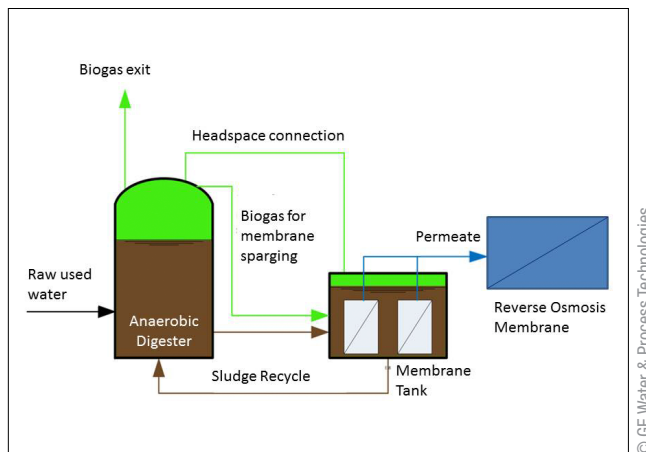


Fig. 2: Process flow for the AnMBR-Reverse Osmosis (RO) configuration

The treatment of used water using anaerobic biological processes is known to have several advantages over the more traditional aerobic systems. These include lower energy requirements, methane gas production, and generation of smaller biomass volumes. Despite these advantages, anaerobic treatment is seldom applied to municipal used water as the influent is diluted and often low in temperature, making the anaerobic process unfeasible.

Recent developments in anaerobic membrane bioreactors (AnMBRs) have, however, opened up new possibilities. Unlike typical anaerobic systems, AnMBRs are able to operate at reduced hydraulic residence times and longer solids residence times.

While GE Water Process & Technologies has been developing AnMBR technology for industrial used water treatment application and had installed its first full-scale AnMBR plant at a brewery located in Delaware in the United States of America in March 2015, relatively limited research has been conducted on the potential of AnMBR technology for municipal used water treatment.

To develop a better understanding of AnMBR performance in the treatment of municipal used water under tropical climate conditions, a team from GE led by Martha Dagneu embarked on a collaborative study with PUB to test-bed GE's ZeeWeed® AnMBR technology at PUB's Ulu Pandan Water Reclamation Plant. The ZeeWeed® AnMBR process is a used water treatment technology that combines anaerobic suspended-growth biological treatment with immersed membrane filtration (Fig. 1).

The demonstration-scale study is being conducted in two phases. The first phase evaluates the impact of the AnMBR process and design parameters on anaerobic membrane performance and effluent quality. In this phase, process efficiency, robustness and long term performance of the AnMBR system is being demonstrated. "So far, the testing showed that a substantial

52% of the total used water chemical oxygen demand (COD) was converted to methane, and quality biogas consisting 85% methane was generated," shares Dagneu. She adds that the AnMBR system will be further optimised to achieve a sustainable flux that will lower the total energy consumption of the process.

In the second phase, a combined AnMBR — Reverse Osmosis (RO) configuration (Fig. 2) will be set up to test the capabilities of the technology to achieve water reclamation and reuse in an energy-efficient manner. Utilising GE's low fouling RO membranes, the RO system will be operated at design parameters to reduce the impact of organic and inorganic constituents in the feedwater on the membrane, and generate stable membrane performance. Emphasis will also be placed on demonstrating the effectiveness of the RO system in reducing ammonium nitrogen concentrations, and determining the effectiveness of membrane clean-in-place systems.

Researchers and affiliation

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Closing the industrial water loop

Upflow anaerobic sludge blanket — ceramic membrane bioreactor process demonstrates potential of recycling industrial used water for non-domestic applications

PUB is constantly on the lookout for innovative technologies to contain the rising costs of treating and producing water, and to identify new sources of water. One example is the on-going collaboration with Meiden Singapore, where a demonstration plant was commissioned at Jurong Water Reclamation Plant to evaluate the feasibility of an integrated Upflow Anaerobic Sludge Blanket — Ceramic Membrane Bioreactor (UASB-CMBR) process to treat and recycle industrial used water for non-domestic use.

The UASB technology taps on anaerobic bacteria to break down organic contaminants in used water. During this process, biogas, which can be used to generate electricity, is produced. In the MBR process that follows, ceramic membranes are used as they are able to handle heavy duty used water containing chemicals and oils, which is challenging to treat (Fig. 1). Combined together, the UASB-CMBR process generates green energy by converting organic components into methane gas and produces less sludge as compared to conventional treatment processes.

Meiden officially began operating the demonstration plant with a treatment capacity of 1 million gallons per day in March 2014 (Fig. 2). Led by Terutake Niwa, the team undertook a one-year testing regime to optimise the plant processes.



Fig. 1: A unit of the ceramic membrane used in the Upflow Anaerobic Sludge Blanket — Ceramic Membrane Bioreactor (UASB-CMBR) plant

In the first stage of testing, Niwa and his colleagues operated the plant at a stable filtration flux of 21 litres per square metre per hour (LMH). Despite the wide fluctuations in the quality of the incoming industrial used water, the plant process was robust enough to consistently produce product water that met the required water quality standard. Energy consumption was also lowered from an initial 1.25 kilowatt hours per cubic metre (kWh/m³) to 1.0 kWh/m³ after process optimisation.

In the second stage which began in December 2014, the plant operating flux was increased to 25 LMH. At the time of publication of this article, the study is still on-going but Niwa has observed a further reduction in energy consumption to 0.85 kWh/m³, with the plant still producing product water of comparable quality to that achieved in the first stage of testing.



Fig. 2: The UASB-CMBR demonstration plant at Jurong Water Reclamation Plant

Moving forward, Meiden plans to increase the operating flux to 30 LMH in the next phase of the study to ascertain if energy consumption can be further reduced. “In this next phase, we also intend to combine the UASB-CMBR process with a reverse osmosis process to better demonstrate the plant’s capabilities in fully recycling industrial used water for future applications,” shares Niwa.

If this demonstration study is proven to be successful, it could allow PUB to potentially to close the water loop for the industrial used water stream in the future.

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Real-time aeration control system to lower energy footprint in used water treatment

Aerobic membrane bioreactor coupled with Tritech online dissolved oxygen monitoring and aeration control system aims to lower energy consumption in the treatment of municipal used water



Fig. 1: Tritech's integrated pilot plant

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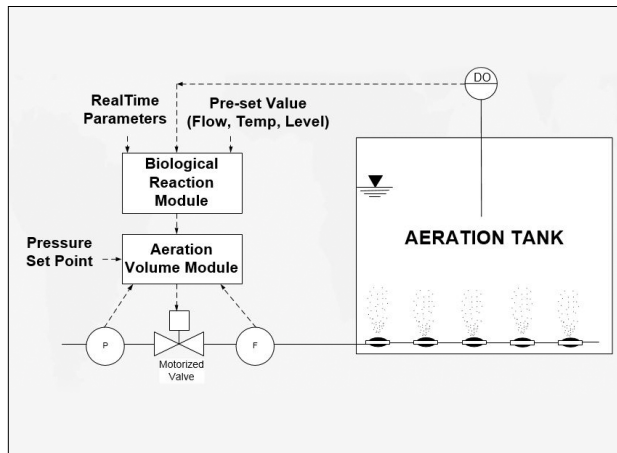


Fig. 2: Process diagram of the online Tritech DoMacs

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The use of aeration is crucial in membrane bioreactor (MBR) systems for used water treatment. Aeration is required for the biological treatment process, where oxygen is introduced into used water to remove nutrients and organic compounds, and in air scouring to minimise fouling of the treatment membranes. This aeration energy required for both processes can contribute to as much as 80% of the total operating energy consumption.

To investigate the possibility of reducing energy consumption in aeration for the MBR process, Tritech Engineering and Testing (Singapore) Pte Ltd is currently test-bedding their pilot plant (Fig. 1) in Ulu Pandan Water Reclamation Plant.

This pilot plant consists of two components – Tritech's proprietary low-energy MBR system, and their Online Dissolved Oxygen Monitoring and Aeration Control System (Tritech DoMacs). Tritech plans to reduce the energy consumption of its low-energy MBR system, which utilises hollow fibre membranes designed and manufactured by the company, by using an intermittent aeration and scouring system. Tritech estimates that this configuration can reduce the aeration energy consumption by between 20% – 50%. The pilot study aims to validate the estimated energy savings, and at the same time, determine the effect of intermittent aeration on membrane scouring efficiency and on mitigating membrane fouling.

In addition to intermittent aeration and scouring, Tritech aims to further reduce aeration energy consumption with the installation of Tritech DoMacs – an integrated real-time water monitoring and aeration control system (Fig. 2). This system analyses and controls the aeration patterns in the treatment process to maximise overall process efficiency. Key parameter sensors such as dissolved oxygen, chemical oxygen demand, and ammonium are integrated with air flow transmitters, analytic instruments, control valves, and variable frequency drives for the blowers to create a real-time

operational control system. Additionally, individual controllers for each blower can be operated by a master control to integrate the individual process control and blower control panels.

Data analysis and comparisons with the performance data in the MBR system before and after the application of Tritech DoMacs will be made in terms of required airflow, aeration efficiency and energy consumption.

Tritech believes that the results of this pilot study can lead to the eventual development of a novel control algorithm and system to lower the energy consumption of MBR systems in used water treatment processes. If the study proves to be a success, this will be good news for the used water industry and for utilities that are on the lookout to evaluate and test suitable technologies that can help to lower energy footprint.

This research is supported under the grant call jointly administered by PUB and SPRING Singapore, through the Environment and Water Industry Programme Office (EWI).

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WATER QUALITY AND SECURITY

As in any country, the quality and security of the water supply is of utmost importance. In order to deal with sources of contamination, Singapore's water scientists constantly strive to improve water quality sampling methodologies through continual innovation in biological and chemical detection methods with one goal in mind: to achieve better, safer and a more secure supply of water.



Measuring toxins released by dead bacteria

Development of an analytical method for endotoxins and determination of their levels in treated water and source water samples



Fig. 1: Extraction of endotoxins from lysed bacteria cells

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Fig. 2: Samples of extracted endotoxins labelled by fluorescent dye

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Bacteria are microscopic organisms that are ubiquitous in the environment. While there are many types of bacteria, they can broadly be classified into two main groups – gram-positive and gram-negative bacteria. Endotoxins – the major constituent of the outer cell membrane of gram-negative bacteria – are a kind of toxin that can potentially be released when bacteria cells undergo lysis.

The risks associated with endotoxins in drinking water are not well-quantified. Limited information about endotoxin levels in drinking water supplies is available as the current endotoxin analytical method – Limulus Amebocyte Lysate (LAL) assay – is an indirect method that does not work well, especially in complicated water matrices.

Sam Li and Huatao Feng from the National University of Singapore are collaborating with PUB to develop an analytical method to reliably determine endotoxin levels in water samples.

Li and Feng will first investigate different methods to extract endotoxins from bacteria (Fig. 1), after which, an analytical technology known as capillary electrophoresis (Fig. 2) will be used to analyse the endotoxins. In the capillary electrophoresis system, a voltage is applied to the system. This causes the endotoxins to move at different velocities through the capillary tube, thus separating one endotoxin from another. As each endotoxin travels through the capillary tube, they are identified by the time they take to reach the detector. Furthermore, the size of each signal registered on the detector also correlates to the amount of each endotoxin that is present in the sample.

As the carbohydrate parts of endotoxins are unique for different bacteria species, Li and Feng also plan to develop a series of methods to analyse the carbohydrate profiles of these endotoxins. With the results obtained, the team hopes to understand the structures of

different endotoxins and develop a rapid method for the identification of bacteria species in water samples.

In addition, to enable quick on-field measurements of water samples, Li and Feng will be investigating the effectiveness of portable analytical instruments (with detection limits that can reach micrograms per litre) as part of the study.

Li and Feng hope to eventually develop an analytical method that will provide reliable results for both pure bacteria cell lines and water samples. “By coupling this with suitable sample pre-treatment methods, endotoxin concentrations in both simple and complex water matrices can be monitored,” says Li. He adds that the method developed in the project will also be able to generate detailed information about the structures and profiles of the endotoxins.

If successful, the development of this new analytical method can help PUB understand the prevalence of endotoxins within the water supply system, and establish effective methods for in-laboratory and on-site analysis of these potentially harmful substances.

This research is funded by the Singapore National Research Foundation under its Environmental & Water Technologies Strategic Research Programme and administered by the Environment & Water Industry Programme Office (EWI).

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Investigating environmental controls of blue-green algae in reservoirs

Study looks at the cyanobacterial toxin-producing species, their toxin production rates and their response to environmental factors



Fig. 1: Using a plankton net to sample cyanobacteria in the reservoir



Fig. 2: Taking water samples from a field experiment for analysis

Reservoirs are rich ecosystems, and home to microscopic organisms like algae and bacteria. While these typically exist as part of the reservoir ecosystem, certain types of algae and bacteria could be harmful to other living organisms. Cyanobacteria or blue-green algae, for example, are found in most reservoirs worldwide and some produce cyanotoxins.

To identify the toxin profiles and levels of cyanobacteria in Singapore's reservoirs, Darren Yeo and his team at the National University of Singapore are conducting a three-year study with co-investigators from the University of Technology Sydney, Cork Institute of Technology, and PUB. The team hopes to identify the cyanotoxin producers in the reservoirs as part of the study.

Using mass spectrometry, algal isolation, and culturing techniques on water samples taken from the reservoirs (Fig. 1), Yeo and his team analysed the different cyanobacteria species found in the samples to determine the species responsible for producing cyanotoxins and their toxin production rates per cell. PUB then verified the identity of the progenitor species by molecular analysis through sequencing of the samples. Real-time quantitative polymerase chain reaction was performed to quantify the cyanotoxin genes and develop primers specific to these genes. These molecular analysis techniques allow for the early and sensitive detection of toxic cyanobacteria at a reduced cost.

The isolated cyanobacteria species were subsequently further examined to determine their growth characteristics and toxin production rates under different environmental conditions of temperature, light and nutrients (nitrogen and phosphorus) (Fig. 2). The team found that growth rates of the isolated cyanobacteria species were positively correlated with nutrient levels and negatively correlated with light intensity. These findings have possible implications for reservoirs in Singapore in terms of nutrient levels and turbidity of the reservoir water.

“Knowing which algal species produce the toxins, and their response to environmental variables will help us develop the appropriate treatment and management actions,” says Yeo. Yeo adds that this knowledge may aid PUB in predicting algae bloom occurrences, so it can potentially manipulate conditions that will be non-conducive to such blooms.

Information from the on-going study will be used to help develop a set of guidelines specific to Singapore. These guidelines will translate algal concentration (measured as algal cells per millilitre) to the risk level of cyanotoxins (i.e. low, medium or high risk). When completed, the final guidelines could allow PUB to make an informed assessment of cyanotoxin risks in our reservoirs and implement the necessary control measures to mitigate these potential risks.

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Monitoring of organic compounds goes 'live'

Pilot-testing of an automated online purge & trap — gas chromatography mass spectrometer to monitor taste and odour compounds in water



Fig. 1: Set-up of the Purge & Trap — Gas Chromatography Mass Spectrometer (P&T-GCMS) system in Chestnut Avenue Waterworks

2-Methylisoborneol (2-MIB) and geosmin are organic compounds produced by microorganisms present in water and soil, usually after environmental triggers such as rainfall following a dry spell. While 2-MIB and geosmin are not toxic, these compounds may cause taste and odour issues.

PUB's Water Quality Office (WQO) currently monitors the concentration of 2-MIB and geosmin in Singapore's raw and treated water supply on a weekly basis using the Purge & Trap — Gas Chromatography Mass Spectrometer (P&T-GCMS) method. This method involves the purging of volatile organic compounds (VOCs) from the water sample and absorption of the purged VOCs on a trap, followed by the separation and quantification of these compounds using the gas chromatography mass spectrometer (GCMS).

To increase the frequency and ease of testing, an online P&T-GCMS system with an automated sampler (Fig. 1) was installed at PUB's Chestnut Avenue Waterworks (CAWW) (Fig. 2). While traditional laboratory P&T-GCMS systems require manual sampling and measurement, the system installed at CAWW is fully automated in its processes — from sampling, to measurement, to the generation of results — and is even capable of sending out alerts to mobile devices. The online P&T-GCMS system was designed to sample and test treated water from the filters and clear water tank outlet. A team comprising members from the WQO and Water Supply (Plants) Department oversaw the system installation and commissioning, and evaluated the performance of the system.

During initial operations, the team discovered that frequent calibration was required as a result of the intensive sampling regime, which was conducted every 48 minutes. As calibration was laborious, time-consuming and disruptive to the automated process, the sampling frequency was adjusted to 4 hours so that calibration could be performed at longer intervals of between 1 to 2 months. These calibrations were later augmented with regular



Fig. 2: Aerial view of Chestnut Avenue Waterworks, where the pilot trial of the P&T-GCMS system was conducted

quality control (QC) tests by the manual injection of QC samples to verify the accuracy of the system results.

To validate the system performance, the results from the online P&T-GCMS system were compared to that of grab water samples sent to WQO for analysis. The team found that the online P&T-GCMS system produced results that were within 20% of WQO's laboratory results about 80% of the time, an outcome that was deemed reasonable given that the results are measured on a parts per trillion level.

In general, the system has proved to be operationally stable thus far. PUB has therefore recently expanded the online sampling regime to include the testing of treated water from the pumping main after leaving CAWW.

Moving forward, PUB plans to improve the manual calibration regime by modifying the online P&T-GCMS system to automatically perform system calibration at fixed intervals. PUB will also be developing the workflow and procedures to operationalise the system, including translation of data from the online system into action plans and alerts.

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WATER TREATMENT

Singapore is committed to ensuring a safe and adequate supply of drinking water for its people. To this end, the development of new technologies to improve water treatment processes for the production of drinking water is of utmost importance. Singapore's water scientists carry out innovative research and development aimed at reducing energy and chemical consumption, and identifying alternative sources of water. This will help to increase supply and safeguard the sustainability of Singapore's water resources for generations to come.



Carbon filters remove micropollutants in water

Production of micropollutant-free and biostable drinking water through an ozone – biologically activated carbon multi-barrier concept



Fig. 1: Ozone and filter pilot systems tested at PUB's waterworks

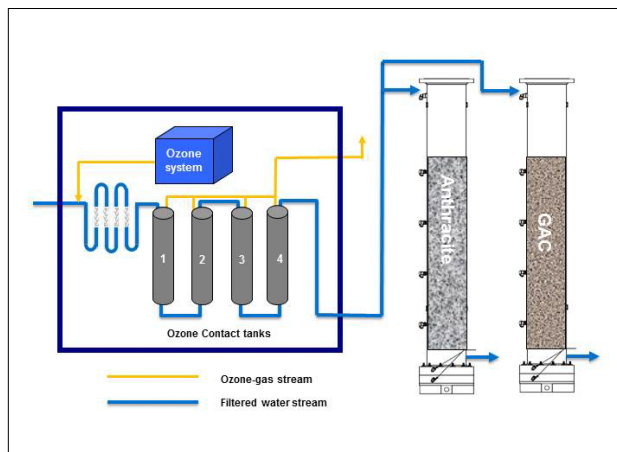


Fig. 2: Schematic of the ozone and filter pilot systems

The use of ozone or ozone with hydrogen peroxide, also known as Advanced Oxidation Process (AOP), as a final disinfection step during water treatment has been proven to be effective in removing various emerging contaminants of interest. This finding was validated by an earlier collaborative study between Xylem and PUB in 2011.

In the application of these technologies in water treatment, oxidation processes such as AOP are normally followed by an additional biofiltration step, which is required to remove the increased Assimilable Organic Carbon (AOC) in the water resulting from the oxidation process. To investigate the synergistic effects between oxidation and biofiltration, Jenny Wang and colleagues from Xylem, together with PUB, embarked on a follow-up study in 2013.

Wang and her team set up the biofilter pilot system next to the existing ozone pilot plant from the 2011 study (Fig. 1 and Fig. 2). The biofilter pilot system was a pre-engineered and pre-assembled system configured to operate with features such as air scouring, backwashing, instrumentation and automation. For this pilot study, two biofilter columns were filled with Granular Activated Carbon (GAC) and anthracite (as an alternative media for comparison) and ozonated water was used as feed to the biofilter columns.

After an initial five-month acclimation phase to allow the filter media to stabilise, tests were conducted to assess the overall performance of the two media under different operating conditions. These included adjustments to both the Empty Bed Contact Time (EBCT) of the filter and the upstream oxidation process (ozone or AOP). This optimisation of EBCT is critical as it will directly impact the design and footprint of the biofilters for future full-scale applications. The filter media were monitored in terms of their AOC removal efficiency, biomass growth, and the removal of taste and odour compounds.

Results of the study demonstrate that both anthracite and GAC (which, following the growth of biomass, is subsequently converted to biofilters) with ozone is able to achieve a high AOC removal efficiency.

“The ozone-GAC biofilter is, however, the superior multi-barrier concept,” says Wang. She explains that in cases of raw water quality deterioration where the injection of hydrogen peroxide was needed, GAC was more effective than anthracite in enhancing the decay and removal of residual peroxide in water. “GAC is also more efficient for taste and odour removal,” Wang adds.

Armed with the knowledge gained from the results thus far, Wang sees further opportunities for her team to optimise the oxidation and biofilter processes in the months to come. She also hopes that the study can provide answers to some key questions, for example, how the AOC is removed by microbial organisms in the filter media.

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Maximising water recovery from used water reclamation

Electrodialysis-reversal-based low-cost low-energy technology aims to maximise water recovery from membrane bioreactor filtrate

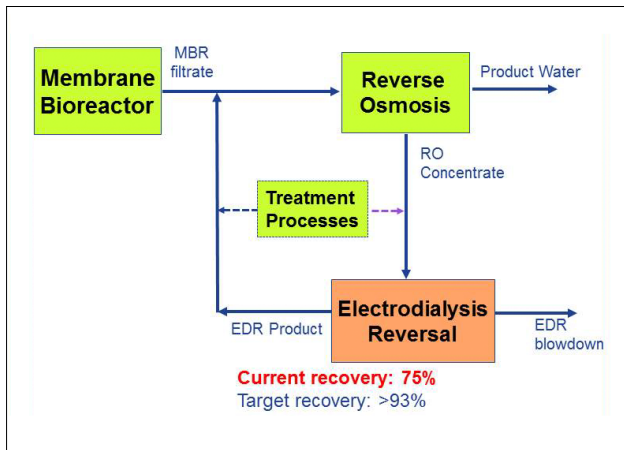


Fig. 1: Process schematic of the electrodialysis reversal (EDR) technology for enhancing NEWater process recovery at Ulu Pandan Water Reclamation Plant

Membrane bioreactor (MBR) systems are increasingly being applied in used water treatment. Coupled with reverse osmosis (RO), the combined process can produce water of NEWater quality standards. Most RO systems for water reuse applications currently operate at about 75% recovery, meaning that 25% of the MBR filtrate is ultimately wasted. In an on-going research program, a team from GE Water & Process Technologies is investigating how existing MBR filtrate treatment processes can be enhanced to achieve filtrate recovery of more than 90% using less energy, and at lower production costs.

Led by Harikrishnan Ramanan, the study comprises laboratory and pilot-scale research to develop cost-efficient used water treatment solutions using the electrodialysis reversal (EDR) process. In this process, the RO concentrate undergoes treatment by EDR to produce a reduced salinity product that can be returned back to the RO inlet for a second pass (Fig. 1). This configuration results in a reduced waste stream and a higher water recovery rate.

Since September 2014, a pilot plant has been in operation in PUB's Ulu Pandan Water Reclamation Plant to carry out preliminary trials and process optimisation studies. Various types of ion-exchange membranes and different spacer designs are being investigated to select the best option for the EDR process (Fig. 2). Different RO membrane types are also being tested to investigate the best possible option for meeting product water quality requirements.

In addition, to evaluate the effects of membrane scaling and fouling and identify possible mitigating solutions, laboratory-scale studies are being carried out in collaboration with researchers from the National University of Singapore (NUS). These include studies on RO and EDR membrane performance and total organic carbon removal technologies such as advanced oxidation process coupled with biological activated process. The research team is also supported by the GE analytical facility in NUS in the areas of



Fig. 2: EDR pilot set-up

water quality analysis and membrane characterisation services. According to Ramanan, these laboratory-scale efforts will help to identify and address potential challenges in meeting product water quality targets, prior to full-scale pilot operation.

“Current results from the laboratory and pilot-scale research are encouraging,” shares Ramanan. “This year, we expect to complete the process optimisation and begin investigating the long term stability of the overall process under realistic scaling and fouling conditions.”

Ramanan believes that data from the pilot operation, coupled with process model development, will facilitate the eventual improvement in the overall process performance of NEWater production by enhancing water recovery and lowering production costs.

This research is funded by the Singapore National Research Foundation under its Environmental & Water Technologies Strategic Research Programme and administered by the Environment & Water Industry Programme Office (EWI).

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Ceramic membranes improve water treatment processes

Advanced membrane filtration process uses flat sheet ceramic membranes at Choa Chu Kang Waterworks



Fig. 1: The ceramic membrane pilot plant at PUB's Choa Chu Kang Waterworks

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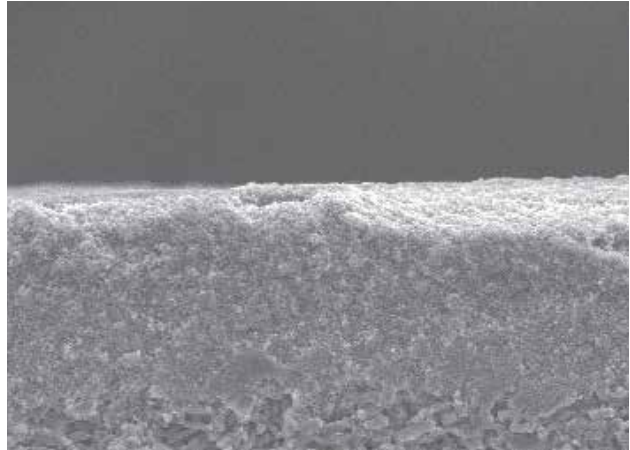


Fig. 2: A scanning electron microscope view of Meiden's ceramic membranes highlighting its active filtration layer

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The use of ceramic membranes in water treatment processes have been gaining popularity as they are robust and can operate at higher flux compared to polymeric membranes. To assess their performance under local conditions, Meiden Singapore test-bedded their ceramic membranes at PUB's Choa Chua Kang Waterworks (Fig. 1). These submerged ceramic flat sheet membranes (Fig. 2) are developed and produced at Meiden's Nagoya plant in Japan.

According to Meiden, unlike ceramic membranes, conventional pressurised and submerged polymeric hollow fibre type membranes encounter frequent fouling issues, particularly when coagulants are used in the treatment process. This leads to reduced water flux, higher cleaning frequencies, and progressively irreversible fouling of the membranes. These higher and increased frequencies of recovery cleaning often lead to earlier replacement of membranes, resulting in higher water production cost.

In this test-bedding project which began in early 2014, the submerged ceramic flat sheet membranes are tested for their filtration performance under coagulated and flocculated feedwater conditions while operating at high permeate water flux. The ability to recover these ceramic membranes under post-production chemical cleaning conditions is also being examined.

Results from this project have been positive thus far, with the ceramic membranes demonstrating their ability to achieve a higher operating flux, excellent removal capabilities for bacteria and viruses, and the ability to meet PUB's drinking water quality standards. In addition, the frequency of fouling for ceramic membranes was observed to be lower than polymeric membranes and the ceramic membranes have a longer lifespan.

The membranes also performed well under simulated test conditions in which they were operated continuously over an extended period of time without cleaning. This was to mimic periods

of continuous high production demand such as in emergencies and drought situations.

"Meiden's ceramic membranes and auxiliary materials have been certified by the National Sanitation Foundation (NSF) International for use in the production of drinking water (NSF Standard 61)," says Noguchi, the research and development (R&D) leader of the Meiden team. Noguchi adds that this NSF mark assures consumers and regulators that Meiden's ceramic membranes have been rigorously tested to comply with all standard requirements.

Moving forward, Meiden will continue testing its ceramic membranes until the end of 2015 to demonstrate the robustness and sustained superior and long-term performance of their ceramic membranes. In addition, Meiden will be relocating its Membrane R&D Centre from Japan to Singapore in July 2015. With this shift, Meiden's ceramic membranes will be assembled in Singapore in the future.

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Agency for Science Technology and Research	Singapore	Singapore Membrane Technology Centre	Singapore
American Water Works Association	USA	Singapore Polytechnic	Singapore
Canadian Water Network	Canada	Singapore University of Technology and Design	Singapore
Centre for Environmental Sensing and Modeling	Singapore	Singapore Water Association	Singapore
Centre for Remote Imaging, Sensing and Processing	Singapore	Singapore-MIT Alliance for Research and Technology	Singapore
Centre for Water Research	Australia	Singapore-Peking-Oxford Research Enterprise for Water Eco-Efficiency	Singapore
Cooperative Research Centres	Australia	Stanford University	USA
Delft University of Technology	Netherlands	Stowa Foundation for Applied Water Research	Netherlands
Deltares	Netherlands	SWELIA Association	France
DHI-NTU Water and Environment Research Centre	Singapore	The Commonwealth Scientific and Industrial Research Organisation	Australia
DVGW-TZW Water Technology Center	Germany	Toray Singapore Water Research Center	Singapore
Global Water Research Coalition	Netherlands	Toshiba Aqua Research Centre	Singapore
Imperial College London	UK	Trent University	Canada
International Desalination Association	USA	Tropical Marine Science Institute	Singapore
International Water Association	UK	Tsinghua University	China
International Water Resources Association	USA	UK Water Industry Research	UK
KAUST Water Desalination and Reuse Center	Saudi Arabia	United States Environmental Protection Agency	USA
KWR Watercycle Research Institute	Netherlands	University of Canterbury	New Zealand
Massachusetts Institute of Technology	USA	University of Illinois at Urbana-Champaign	USA
Michigan State University	USA	University of Maryland	USA
Monash University	Australia	University of New South Wales	Australia
Nanyang Environment and Water Research Institute	Singapore	University of North Carolina	USA
Nanyang Technological University	Singapore	University of Oxford	UK
National Centre of Excellence in Desalination	Australia	University of Queensland	Australia
National University of Singapore	Singapore	University of Waterloo	Canada
New Energy and Industrial Technology Development Organisation	Japan	University of Western Australia	Australia
Ngee Ann Polytechnic Centre of Innovation for Environmental & Water Technology	Singapore	University of Toronto	Canada
NUS-Environmental Research Institute	Singapore	Water Environment Research Foundation	USA
Pôle EAU	France	Water Research Commission	South Africa
Queensland Government	Australia	Water Research Foundation	USA
Sandia National Laboratories	USA	Water Services Association of Australia	Australia
		WaterReuse Research Foundation	USA
		World Health Organisation	Switzerland

Water Utilities and Companies

Affordable Water	New Zealand	Hyflux	Singapore
Aqleo	Singapore	Institute of Occupational Medicine Singapore	Singapore
Aquaporin A/S	Denmark	Integrated Land Management	USA
Amiad Filtration Systems	Israel	iWOW Connections	Singapore
Anaergia	USA	Joyce River Hi-Tech Technologies	Singapore
Aromatrix Technologies	Hong Kong	Johnson Pacific	Singapore
Asahi Kasei Corporation	Japan	Kemira	Finland
Awa Instruments	Singapore	Keppel Seghers	Singapore
BASF SE	Germany	Kinrot Holdings	Israel
Baleen Filters	Australia	Koch Membrane System	USA
Becton Dickinson	USA	Kuraray	Japan
Biofuel Research	Singapore	Kurita Water Industries	Japan
Black & Veatch Corporation	USA	K-One Industries	Singapore
Blue I Water Technologies	Netherlands	Lighthouse Integral	Singapore
Boerger Pumps Asia	Israel	Liqtech	USA
Bousted Salcon Water Solutions	Singapore	Mann+Hummel Ultra-Flo	Singapore
Camp Dresser & Mckee	Singapore	Mattenplant	Singapore
Ceraflo	USA	Meiden Singapore	Singapore
CH2M	USA	Mekorot	Israel
CPG Corporation	Singapore	Membrane Instruments and Technology	Singapore
Daily Life Renewable Energy	Singapore	Memstar Technology	Singapore
Darco Water Technologies	Singapore	Metawater	Japan
DHI Water & Environment	Singapore	Mitsubishi	Japan
Dow Chemical Company	USA	Moya Dayen	Singapore
Dragon Water Group	Germany	MWH Asia Pacific	Australia
DSO National Laboratories	Singapore	Natflow	Singapore
D-RON Singapore	Singapore	Nitto Denko Corporation	Japan
ecoWise Technologists & Engineers	Singapore	Optiqua Technologies	Singapore
Endress+Hauser Instruments International	Switzerland	Orange County Water District	USA
Envipure	Singapore	PulverDryer Technologies	USA
Enviro Pro Green Innovation	Singapore	PWN Technologies	Netherlands
Envirotech and Consultancy	Singapore	Rand Water	South Africa
Evoqua Water Technologies	USA	Rehau Unlimited Polymer Solutions	Germany
ExxonMobil Asia Pacific	Singapore	Saline Water Conversion Corporation	Saudi Arabia
Fluigen	Singapore	Semcorp Industries	Singapore
GE Water & Process Technologies	USA	SUEZ Environnement	France
Global Water Intelligence	UK	Tritech Engineering and Testing (Singapore) Pte. Ltd.	Singapore
Glowtec Environmental Group	Singapore	Trojan Technologies	Canada
GMF-Gouda Singapore	Netherlands	United Engineers	Singapore
GrahamTek Nuwater	Singapore	United Envirotech	Singapore
Grundfos	Denmark	Veolia Environment	France
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Huber Technology	Germany	Water And Sewerage Authority	Trinidad & Tobago
Hydrovision Asia	Singapore	Water Optics Technology	Singapore
		WH2O Technology	Singapore
		Wisewater	Singapore
		Xylem	USA
		ZWEEC Analytics	Singapore



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