INNOVATION IN WATER SINGAPORE

An R&D publication of PUB,
Singapore's National Water Agency

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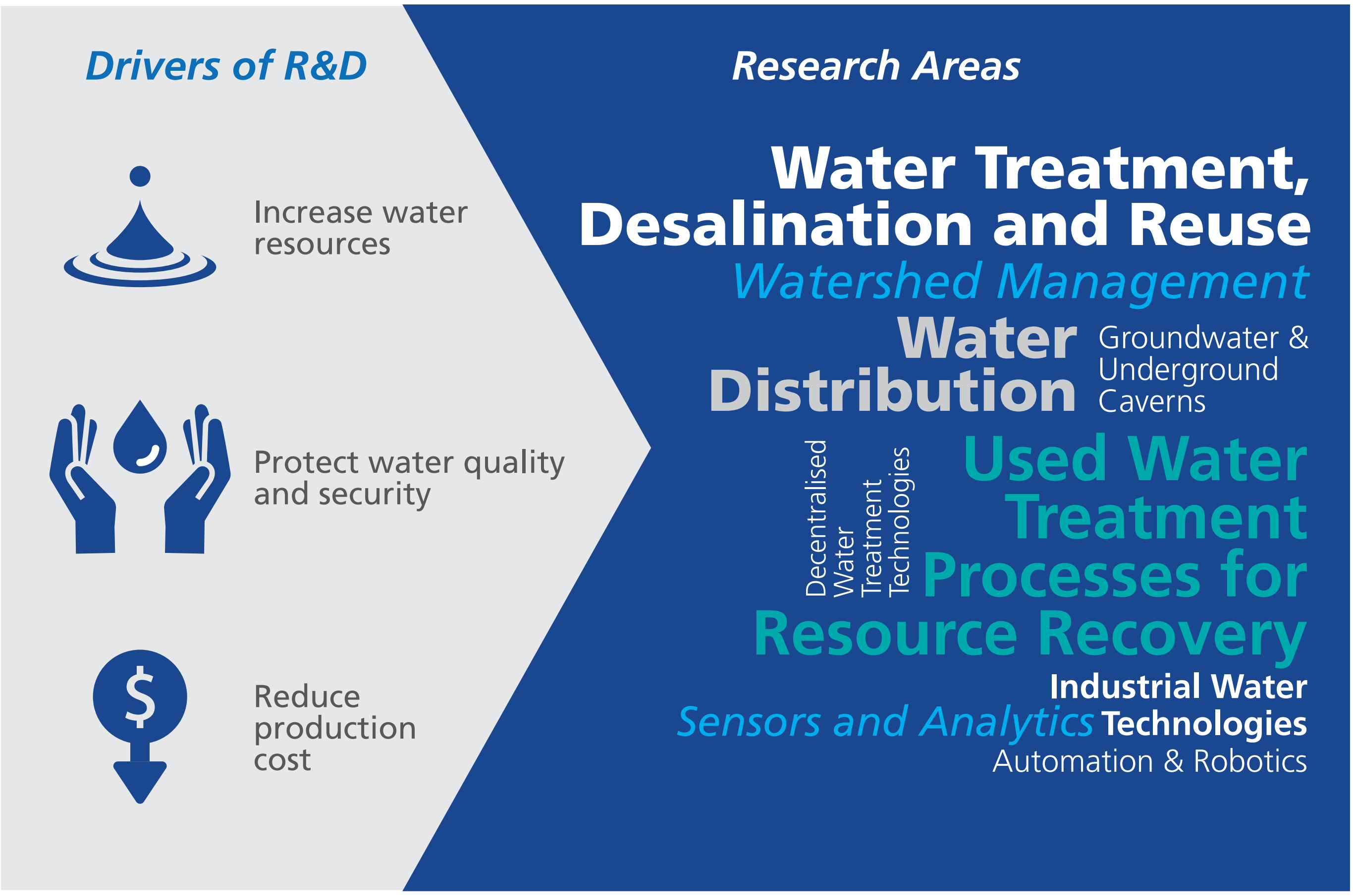
Thank you for picking up the latest edition of *Innovation in Water | Singapore.* We hope you will enjoy reading about some of the latest, cutting-edge water research carried out in Singapore.

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

Opportunities for collaborative research abound for partners in the water and related industries, universities, and research institutions (local and overseas) who share our objective of securing a safe and sustainable supply of water through use-inspired fundamental research, application and technological development, as well as investment in process improvement, knowledge management and implementation. Outlined below are the goals we aim to achieve through the application of innovative solutions across PUB's key focus areas.

You may find out more information on PUB's research and development programme at www.pub.gov.sg/research. To begin your partnership with PUB, please contact us at PUB_Research@pub.gov.sg.



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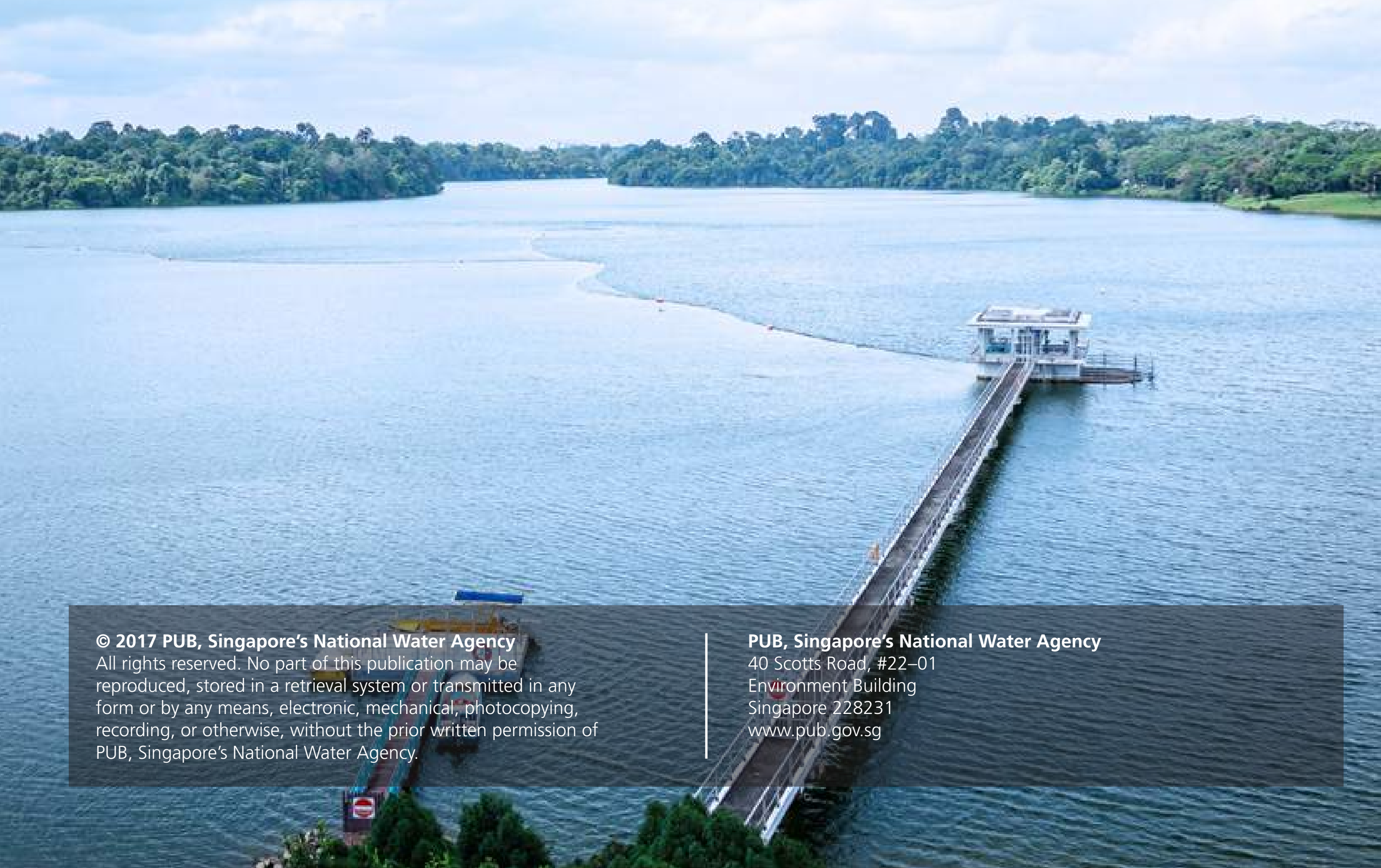

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Paving the way for water innovation
Water is both a key strategic and economic asset in Singapore. With water technology as a key pillar of economic growth, PUB, Singapore's National Water Agency and the Economic Development Board work closely with other government agencies, companies and research institutes to develop Singapore into a thriving global hydrohub. Steered by a clear focus on innovation, we offer a range of support to companies that comprises research funding, graduate scholarships and test-bed opportunities for cutting-edge solutions.
Let us help bring your innovations to fruition.
EDB singapore
PUB SINGAPORE'S NATIONAL WATER AGENCY

Message from PUB

Singapore's water story has been one of its successful chapters in its 50 years of independence. In that time, we have turned our water vulnerability into a strategic asset, diversifying and strengthening our water supply through timely and shrewd investments.

Still, challenges lie ahead. Our weather has become increasingly erratic, and our population and economy will continue to grow and require more water. To keep our water supply robust, sustainable and affordable, we must continue to invest in technology.

We must pursue applied research, and find ways to turn findings from laboratory experiments into demonstrable technology, and into commercially viable solutions. In this issue, we outline how Singapore spearheads the translation of water research and technologies to develop an intelligent and sustainable water management system.

The nuts and bolts of bringing water technologies to maturity in the marketplace are described through examples, such as the development of a microbial electrochemical sensor, pressure retarded osmosis and biomimetic membrane technologies, in our *Feature* article.

In *People in Water Research*, Professor Gary Amy, a visiting professor at the National University of Singapore and coordinator of Singapore's Membrane Science and Technology Consortium, shares his insights and views on the complex relationships among water, energy, waste and materials, related emerging technologies and Singapore's role in translating these technologies.

Facilities Focus shines the spotlight on Singapore's water eco-system and zeroes in on its translation facilities. The Separation Technologies Applied Research and Translation Centre, for example, aims to develop and commercialise innovative separation and filtration technologies, including membranes, to ease companies through their technology adoption journey.

Over the years, with the support of our industry and academic partners, we have poured more than S$356 million into over 510 research projects to find new water solutions, building new connections and strengthening collaborations in the process. Some of these partnerships are detailed in the *Research Highlights.*

In the long term, it is critical for new and future officers joining PUB to appreciate the importance of research and technology in strengthening Singapore's water resilience. To this end, we have involved our scholars from our National Environment and Water (NEW) Scholarship Programme in the writing of the articles in this issue, allowing them to gain first-hand knowledge on technology trials and bridge the gap between academic theories and real-life applications.

We hope that this issue of *Innovation in Water* will deepen your understanding of water research and technology adoption, and inspire you to join us in our mission to ensure an efficient, adequate and sustainable supply of water for Singapore.

Hoo Eng Jek Richard
Deputy Chief Executive (Policy and Development)
PUB, Singapore's National Water Agency

Accelerating the implementation of innovative water solutions through technological translation

Meeting Singapore's water needs

Singapore is the definition of a country that punches above its weight. Despite its small size, it is amongst the world's most economically-advanced nations. Its success, however, relies on the careful management of water resources to meet the twin demands of urbanisation and economic growth. With a population of more than 5 million people, Singapore uses approximately 430 million gallons of water each day.

So far, Singapore's innovative water management strategies have carried the day. Even during the 1970s, when the water industry was considered technologically conservative, Singapore understood the need for unconventional water sources to augment its supplies from local catchments. Since then, the government has pursued and adopted new technologies, and established a targeted research and development (R&D) programme to safeguard Singapore's water future.

Take Singapore's history with membrane technology. The technology was costly and unreliable when Singapore first considered the option of recycling used water in the 1970s, but it improved steadily over the next 20 years. In the 1990s when the technology's cost and performance had improved considerably, PUB seized the opportunity to develop NEWater – high grade, ultra-clean recycled water. Introduced in 2003 after extensive R&D, NEWater has passed more than 150,000 scientific tests, exceeding the World Health Organisation's drinking water quality standards, and meets up to 40 per cent of Singapore's water needs today.

The plan is to expand its capacity by 2060 to meet up to 55 per cent of future water demand. To realise this goal, PUB is streamlining Singapore's used water infrastructure to collect every drop of used water for treatment and reuse. The advanced Deep Tunnel Sewerage System (DTSS) conveys used water by gravity to centralised water reclamation plants (WRPs) for treatment. The treated effluent is then either discharged to sea or further purified into NEWater.

Phase One of the DTSS was completed in 2008 and covers the eastern and northern parts of Singapore. Phase Two, which is projected to be completed by 2025, will extend the system to western Singapore, including the downtown area and upcoming developments such as Tengah Town. After the completion of the DTSS and its three centralised WRPs, PUB will progressively decommission the existing Ulu Pandan and Jurong WRPs and intermediate pumping stations to make way for other developments.

NEWater, however, is just one arrow in Singapore's quiver. In 2005, PUB introduced desalinated water as a National Tap with the opening of the SingSpring Desalination Plant. Tuaspring, Singapore's second desalination plant, began operations in 2013. Plans are in place for three more plants to be built in Tuas, Marina East and Jurong Island by 2020 to further boost the country's drought resilience and strengthen water security. By 2060, desalination will meet up to 30 per cent of Singapore's water needs.

These efforts have created a robust, diversified and sustainable supply of water known as the Four National Taps: water from local catchments; imported water; NEWater; and desalinated water. PUB has not rested on its laurels, however, and continues to strengthen these taps to prepare for Singapore's future. Water demand is expected to be more than twice of the current consumption by 2060.

PUB also supports the development of innovative water technologies through funds from PUB's R&D programme and the National Research Foundation (NRF). The latter, which aids local R&D projects with an eye to developing Singapore as a global hydrohub, is administered by PUB and the Singapore Economic Development Board (EDB).

PUB's R&D programme

As Singapore's national water agency, PUB is responsible for managing all aspects of Singapore's water resources, and developing the nation's water R&D programmes. Formed in 2004, PUB's water R&D programme helps water companies, utilities and local and global research institutes to develop solutions in 10 key fields that span the entire water loop: biological processes; chemical and redox technologies; desalination and water reuse; sludge and brine management; automation and robotics; watershed management; water quality analytics and water distribution; groundwater and underground caverns; decentralised water treatment technologies; and industrial water technologies.

These efforts, which are guided by a roadmap that directs PUB's R&D investments, aim to meet four specific goals: increase Singapore's water resources; reduce production costs; enhance water quality and security; and grow the water industry. To date, the R&D programme has supported more than 510 projects with a collective value of $356 million.

Although PUB focuses on operationally-ready technologies, its support spans the entire water R&D continuum: from idea conceptualisation and basic research to applied research, pilot scale demonstration, test-bedding and commercialisation. By bridging fundamental "upstream" research and practical "downstream" applications, PUB's R&D programme brings translational value to its collaborative partnerships.

Translation of ready technologies

In fact, water firms, organisations and researchers have flocked to Singapore as PUB makes available its extensive infrastructure, comprising waterworks, water reclamation plants, NEWater factories, reservoirs, stormwater canals and even water pipes, for the testing and scaling up of new technologies. It also provides feedback on the products and advice on operational issues.

This allows water technology developers to trial and improve their inventions under actual operating conditions, secure crucial operational data to show that their products are safe, and gain insights into end-user needs to craft commercially-relevant solutions. With PUB's financial help, facilities and expertise, its partners can share the cost of R&D and reduce the risks of developing a new product.

It is in PUB's interests that innovative water solutions take the most efficient route to market. The sooner a technology is fine-tuned and commercially available, the sooner it can help to improve PUB's operations, increase market competition and expand consumer choice. To date, PUB has supported 172 test-bedding projects and four demonstration-scale projects in its facilities, in addition to laboratory-scale and pilot-scale research projects.

Singapore's burgeoning water sector, which now comprises 180 companies and more than 20 research institutes, contributes over $2.2 billion in value-add to the country's gross domestic product and has created some 14,000 jobs.

Opportunities for collaboration

Whether based locally or internationally, companies, universities, research institutions and even individuals who want to research and develop innovative water technologies will find plenty of opportunities in Singapore.

PUB warmly welcomes all who share Singapore's goal of improving water management through inspired fundamental and applied R&D, knowledge sharing and technological implementation. Join us in creating a water sustainable nation for years to come.

Translating water technologies into practice

Over the years, funding and resources have been poured into water research and development (R&D). Together with prudent water management strategies, this has helped Singapore address its water challenges, and transformed Singapore into a global hydrohub. While Singapore's unwavering efforts in research continue to be a crucial part of its march towards water sustainability, another key aspect is the scaling up and translation of ground-breaking discoveries so they can be put into operational practice.

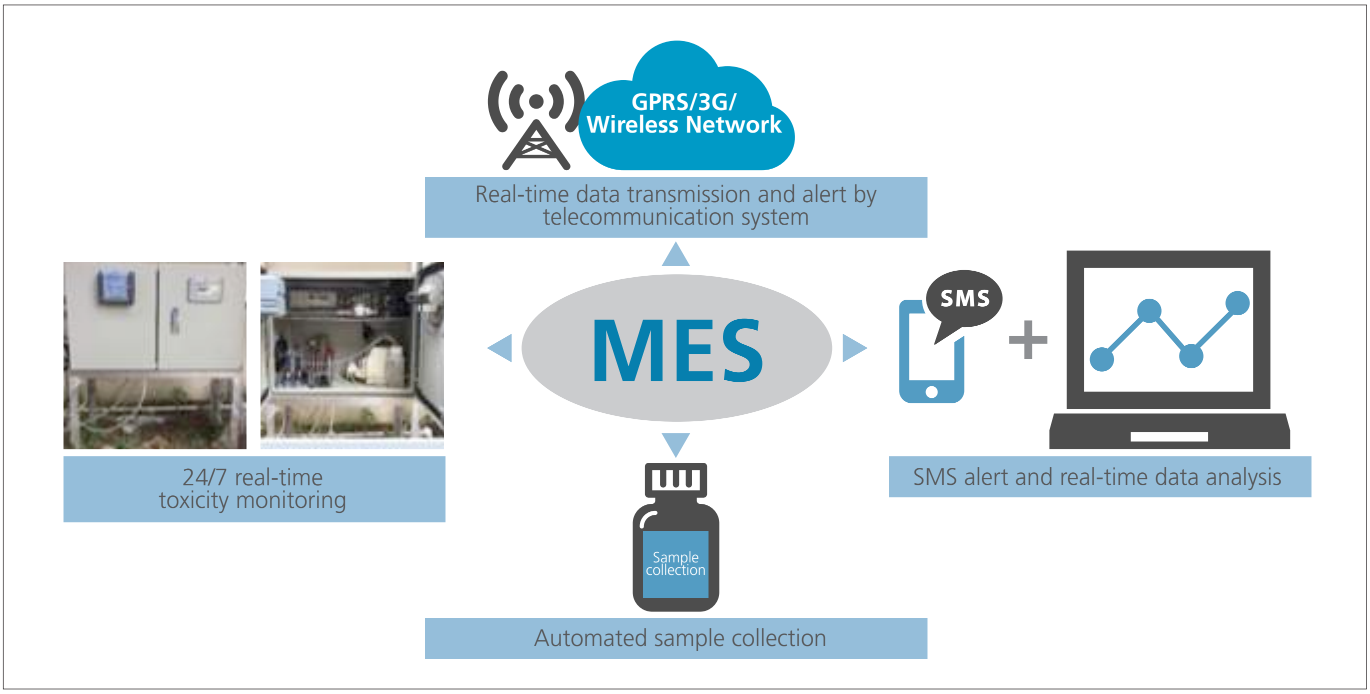

Fig. 1: The microbial electrochemical sensor (MES) toxicity monitoring system alerts operators, which alerts operators instantly when pollutants are detected

From laboratory to implementation

Since water was identified as a key growth industry in 2006, $670 million in R&D funding has been committed to foster technologies and create a thriving research community in Singapore over 15 years. As the increasingly vibrant local water industry continues to develop more water technologies, the need to bridge the gap between laboratory-scale research and its commercialisation will correspondingly become more urgent.

In October 2016, national water agency PUB launched a unique grant call for proposals under the Competitive Research Programme for Water to meet this need. A total grant of up to $25 million was allocated to fund projects along two tracks: the development of novel technologies; and the translation of existing laboratory-scale technologies for eventual implementation. In particular, the latter track – technological translation – has traditionally received less attention, and represents a bold push towards the commercial implementation of new and emerging technologies.

Under this track, companies and technology providers can support emerging technologies and apply for funding to further develop and commercialise them. The goal is to commercialise some, if not all, of the 18 existing research technologies identified for translation within the next five years. Key among these technologies are a microbial electrochemical sensor (MES) system to detect pollutants in our sewers, pressure retarded osmosis (PRO) membranes, and biomimetic membranes.

Online toxicity sensors for the sewer network

When pollutants such as heavy metals and cyanide are accidentally or illegally discharged into Singapore's sewer network, they can affect the biological treatment processes of downstream used water treatment plants. PUB has been working with a team from the National University of Singapore (NUS), led by Ng How Yong, to develop a responsive and inexpensive MES system (Fig. 1) that can detect such discharges quickly for timely implementation of downstream intervention measures.

Interestingly, the system was initially intended as a microbial fuel cell. The researchers thought that the cell could increase the efficiency of power generation for used water treatment, but tests showed that its resistance actually restricted power outputs considerably. Undeterred by the setback, together with PUB, the team explored alternative options where the same electrochemical principles could apply, and discovered that the technology could be used as a toxicity sensor instead. This led to the development of the current MES system where high concentrations of heavy metals and cyanide in used water will cause the electrical voltage of the MES to drop, triggering an alert to PUB.

So far, five units of the MES prototype system have been installed at industrial trade effluent sites for real-time monitoring of used water discharge. In the next few months, 10 more units will be installed at various sites in the Tuas and Woodlands industrial estates.

Harnessing osmotic power through PRO

PRO is a method to harvest energy from a system that has two streams of water with different salinities and pressures. Due to the difference in water potential, water spontaneously travels across a semi-permeable membrane from a low-salinity solution (such as NEWater brine) to a high-salinity solution (such as seawater reverse osmosis (SWRO) brine). The net volume increase in the high-pressure compartment of the high-salinity solution can be tapped on, for example, to generate electricity via energy transfer devices, or to offset the high pressure required for SWRO by using pressure exchangers.

A key benefit of PRO technology is that it is a source of renewable energy, and could mitigate environmental waste disposal issues associated with high-salinity brines. In Singapore, the technology could be applied using the brines from seawater desalination and NEWater production respectively (Fig. 2).

Currently, researchers in the field are focused on developing PRO membranes that can withstand the high pressure system and thus produce more power. A team led by Neal Chung Tai-Shung from NUS has created flat sheet membranes and hollow fibre membranes that can withstand pressures of up to 22 bar and 20 bar respectively.

Separately, another team led by Wang Rong at Nanyang Technological University (NTU) has developed novel PRO hollow fibre membranes that showed long-term stable performance under a pressure of 15 bar (they were tested for more than 200 hours). The team is also using aminosilane to produce these anti-fouling thin film composite PRO membranes. A benefit of aminosilane is that it can enhance the hydrophilicity of membranes, increasing their water permeability and thus creating higher power density.

Moving forward, the teams will need to scale up their research to demonstrate their PRO technologies in a pilot plant with a capacity of 200 – 250 cubic metres per day (m^3/day), to assess the membranes' long-term performance.

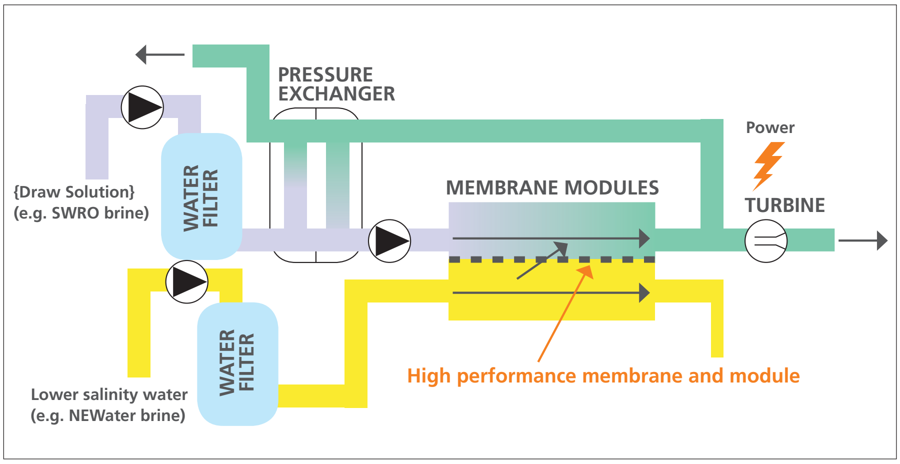

Fig. 2: The concept of pressure retarded osmosis (PRO) for the generation of osmotic power

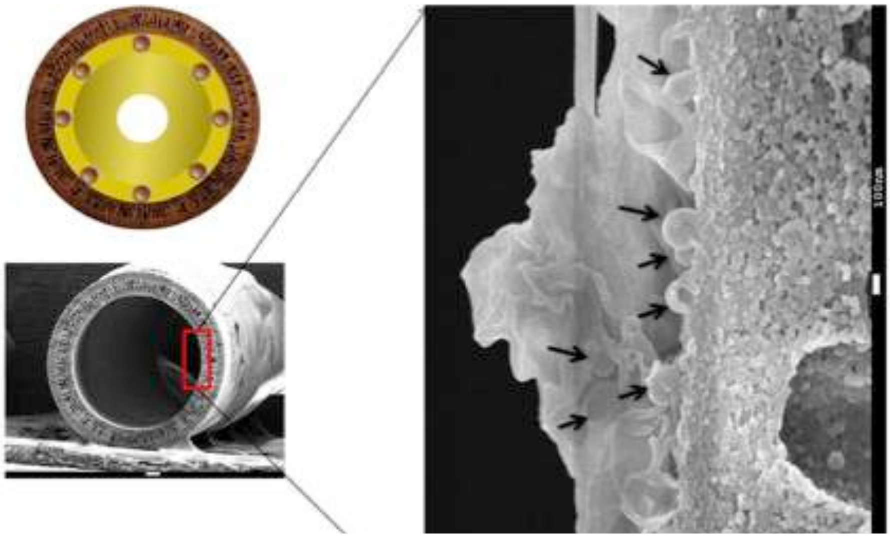

Fig. 3: Aquaporin-based biomimetic membranes in hollow fibre configuration

Mimicking nature in biomimetic membranes

Aquaporins are water channel proteins which are found naturally in living organisms. These protein channels act like nature's own water filtration system: they allow water to flow through them while remaining impermeable to other molecules. Aiming to replicate this natural phenomenon, Singapore has been developing novel membranes embedded with aquaporins for various water treatment applications. These aquaporin-based biomimetic membranes (ABMs) are expected to exhibit higher permeability and selectivity for water molecules, and thus require lower operating pressures for the filtration process. This would potentially reduce water production's energy consumption and costs.

A group of researchers from NTU, led by Wang, successfully fabricated flat sheet ABMs with 40 per cent higher water permeability than commercial reverse osmosis (RO) membranes using a method called interfacial polymerisation. This method protects the membranes' aquaporins through the polymer matrix of the selective layer, so that their function is not affected by the harsh conditions of the feed water. Moreover, the membrane's structure gives it sufficient mechanical strength to withstand high hydraulic pressures, increasing its durability.

Building on this success, the team further developed ABMs with a hollow fibre configuration (Fig. 3). The membranes were tested for different applications such as RO, PRO and forward osmosis, and the results showed that they had significantly higher water permeability than conventional polymeric membranes while maintaining good salt rejection.

However, for large scale implementation, ABM modules need to be further developed and optimised. Plans for the construction of a pilot plant with a capacity of 10 m^3/day are in place, to test the technology for both desalination and water reclamation applications.

Due to its lack of natural water resources, Singapore was thrust into a water predicament from the start of its independence. Technological advancements over the years have given the nation a commendable degree of water security and sustainability, but the need for innovative water technologies is still crucial, especially as the country's water demand is expected to more than double by 2060. Technologies that meet our needs must be ready for implementation within a reasonable timeframe or risk losing their relevance and advantage.

By creating opportunities and keeping resources at hand, Singapore is ready to spearhead efforts that will translate its technological dreams into reality, and achieve the ultimate end-goal of R&D: commercial implementation.

People in Water Research

Gary L. Amy

Visiting Professor, National University of Singapore

A generational challenge and opportunity: The water-energy-waste-materials nexus

I believe that the water-energy nexus is a generational challenge for megacities throughout the world, including Singapore. This nexus acknowledges that water and used water purification processes and systems need energy, and energy and power processes and systems require water. What we call the water-energy-waste nexus is simply an extension of this water-energy relationship that recognises waste as a potential resource. For example, more water can be recovered from waste streams and energy can also be harvested from used water and waste streams. Beyond water and energy, valuable materials can be reclaimed from waste streams, such as lithium from seawater brines and phosphorus from municipal used water. In Singapore, the seawater reverse osmosis (RO) brine from desalination, biosolids from secondary used water treatment and NEWater brine from NEWater production are waste streams that could be further exploited.

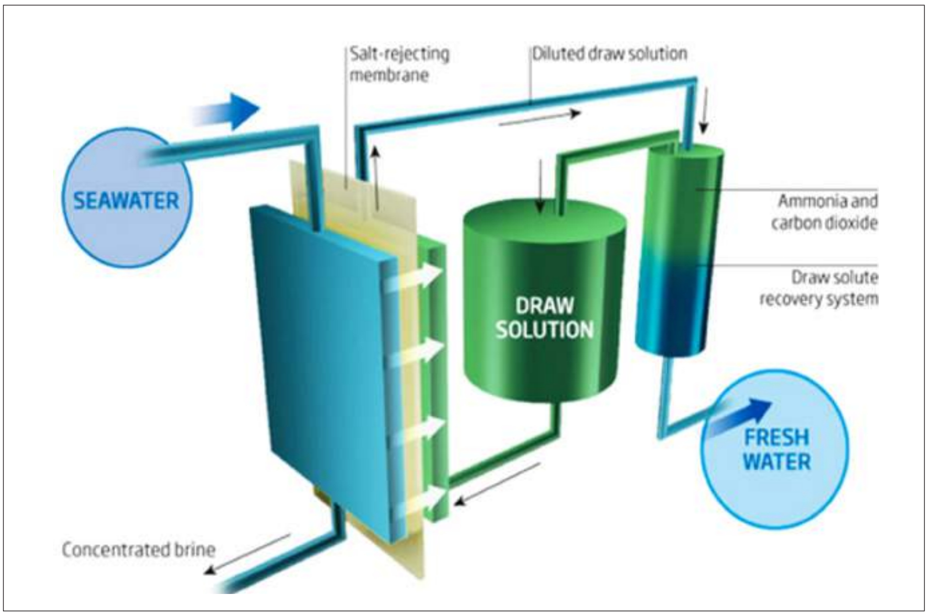

Fig. 1: Schematic of the forward osmosis desalination process

Globally, we are already witnessing a paradigm shift in the municipal used water field. A municipal used water treatment plant is also seen as a resource recovery plant that can extract water for reuse, biogas for energy, and nutrients and fertilisers from municipal used water. We could see a similar paradigm shift in exploiting the resource potential of saline water and waste brine, which could offer more water and energy and valuable materials.

Emerging solutions: Separation technologies and innovative materials on the horizon

Translational research will be crucial in realising this resource potential of saline water and waste brine. While a number of related emerging separation technologies have reached or are near the proof-of-concept stage, these have been "stuck" on the technology-development pathway because of various challenges that need to be overcome through scientific breakthroughs in material science and/or process and module configurations. The emerging saline water and brine technologies that hold the greatest promise include forward osmosis (FO) (Fig. 1), electrodeionisation (Fig. 2), capacitive deionisation (CDI), membrane CDI, vacuum membrane distillation, pressure retarded osmosis (PRO), reverse electrodialysis and various process hybrids. As we advance these technologies, our efforts have to be benchmarked against established separation technologies, namely, seawater RO for desalination applications, and brackish water RO for brackish groundwater treatment. Equally important are new niche applications of emerging technologies where the effectiveness of RO is limited, for example in the processing of hyper-saline waters such as oil-and-gas produced water and brine. Priority should be placed on further translating emerging technologies that can surpass current benchmarks in economic, energetics and/or environmental parameters, or that clearly provide a solution to operational needs. In Singapore, PUB has supported the development of a low-energy desalination hybrid involving electrodialysis and continuous electrodeionisation.

Beside emerging processes, emerging materials of interest include water and ion protein and synthetic channels, ultra-high permeability membranes, anti-fouling membranes, novel FO draw solutions,

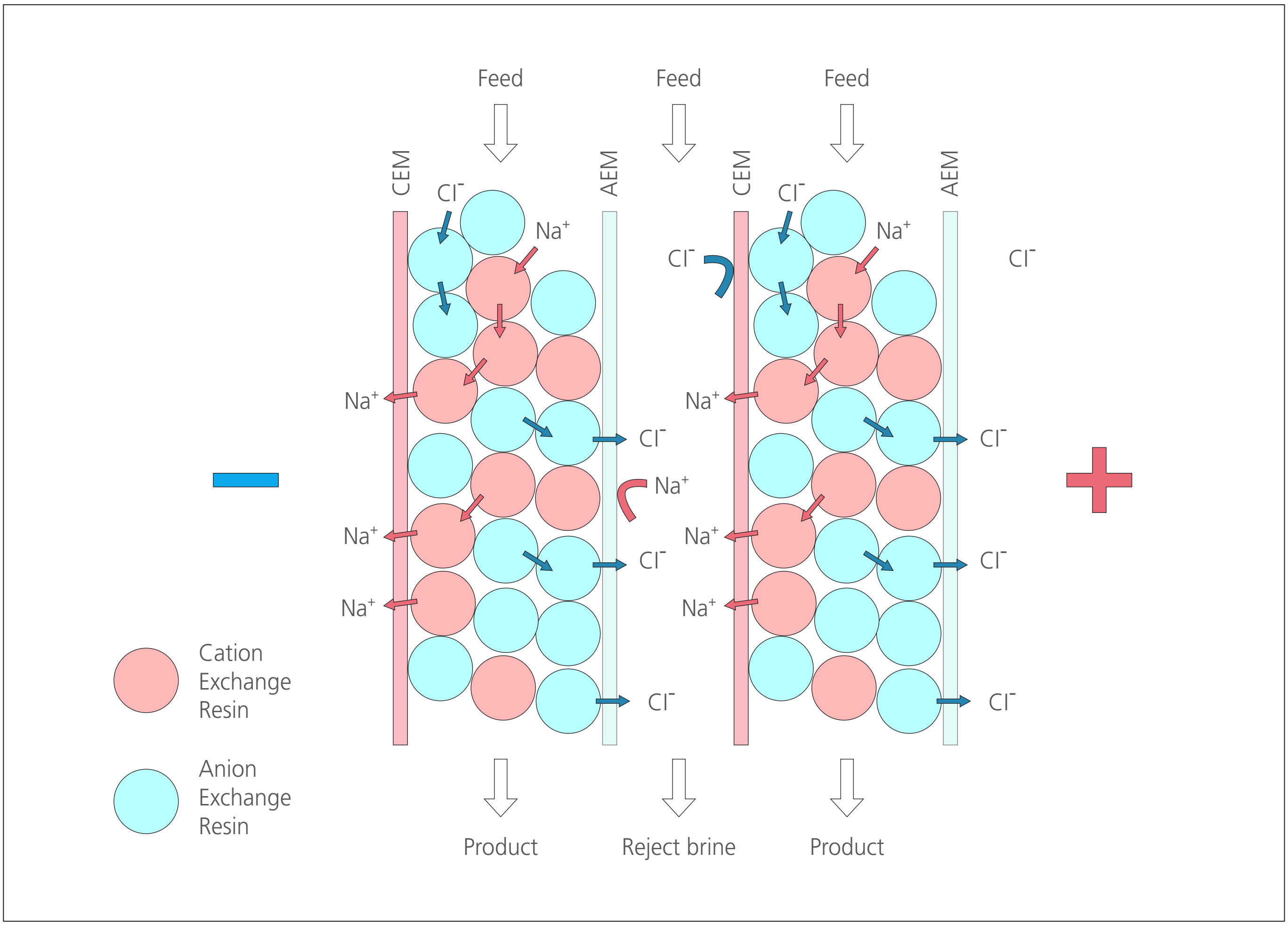

Fig. 2: Schematic of the electrodeionisation process

new-generation salinity gradient process membranes, high-capacity electrode materials and selective adsorbents for the extraction of valuable materials. PUB is supporting research for several emerging processes and materials with identified limitations that can be overcome through research and development. These include PRO, where new higher-power density and lower-fouling PRO membranes could improve process energetics and costs, as well as membrane fabrication techniques to incorporate synthetic water / ion channels within a polymeric matrix and provide a new generation of membranes with high water or ion permeability and membrane stability.

Translating potential: Singapore as a future hub for membrane technologies

Singapore has a unique opportunity to advance these emerging technologies through its proactive funding programmes and clusters of research excellence in the public, academic and private sectors. PUB has embraced membrane technology in seawater desalination and NEWater production, and has demonstrated an interest in membrane bioreactor technology. It is noteworthy that many of the country's research activities and needs involve membrane-related water technologies, where the key interests are in lowering the energy footprint and/or energy-harvesting to offset energy requirements. Clusters of membrane research excellence already exist in Singapore, including the NUS' Membrane Science and Technology Consortium, Nanyang Technological University's Singapore Membrane Technology Centre, the Separation Technologies Applied Research and Translation (START) Centre and Ngee Ann Polytechnic's Environmental and Water Technology Centre of Innovation (EWT-COI). In particular, START and EWT-COI are involved in translational research that moves membrane technologies from proof-of-concept to technology development and demonstration, and towards commercialisation. Over the past decade, Singapore has gained recognition as a global water hub, and there is now an opportunity for it to be known as a global membrane hub within the water arena.

Dr Gary Amy is a Visiting Professor in Chemical and Biomolecular Engineering at the National University of Singapore (NUS), where he also serves as coordinator of the NUS Membrane Science and Technology Consortium (MSTC). In the United States, he is the Dean's Distinguished Professor in the College of Engineering, Computing and Applied Sciences at Clemson University as well as coordinator of the Clemson Water-Energy Consortium. He was formerly the founding director of the Water Desalination and Reuse Center at the King Abdullah University of Science and Technology. His expertise is in novel membrane technologies for seawater desalination and wastewater reuse.

Taking research to the market

Turn on the tap in your home today and you can get as much water as you need. Since Singapore's independence, PUB has developed a robust and sustainable supply of water over the years. To continue to provide Singapore with an efficient, adequate and sustainable supply of water even in the face of future challenges, today's water research must be translated into tomorrow's water solutions. This article focuses on key academic and translation facilities in Singapore that enable this process.

© Separation Technologies Applied Research and Translation Centre

Singapore has come a long way to establish itself as a vibrant and competitive water hub, conducive to the growth of innovative ideas. To continue to provide Singapore with an efficient, adequate and sustainable supply of water even in the face of future challenges, today's water research must be translated into tomorrow's water solutions. The National Research Foundation has committed an additional $200 million in funding over the next five years, as Singapore strengthens its position as a global hydrohub for the research, development and commercialisation of new and innovative water technologies. This brings the government's total funding of the water sector to $670 million over 15 years since it was recognised as a key growth sector in 2006.

Too often, researchers face hurdles in adapting their work from the laboratory to the marketplace, or they simply do not know how to do so. Firms, especially start-ups, also have trouble navigating the 'valley of death' as they attempt to develop their technologies for commercial use. They may have problems finding enough skilled employees with the necessary technical expertise, or lack capital and infrastructure to test their technologies in real-world settings. To help ensure that efforts in fundamental research are utilised and promising technologies are commercialised, Singapore presently has several academic and translation facilities.

The Separation Technologies Applied Research and Translation (START) Centre is a national facility that helps to bring separation-related technologies to the market. Located at CleanTech Park, Singapore's first technology park for water and green-technology firms, it links Singapore's numerous research institutes to the water industry and nurtures these connections, providing a rigorous, real-life setting for proof-of-concept systems to be tested. START brings together 15 to 20 industry experts who have backgrounds in materials science and chemical, mechanical and electrical engineering, as well as illustrious careers in renowned companies, to help select promising water separation-related technologies from Singapore's various research institutes. It also offers membrane fabrication equipment, systems design and development assistance as well as real-life pilot-testing facilities where technologies can be evaluated in a variety of scenarios to ensure their product capability and feasibility.

Fig. 1: The laboratory prototype of the membrane-based evaporative cooler (MEC) system (left), compared to a conventional cooling tower (right)

Additionally, START sources for industry partners to scale up polished products and bring them to market. "This initiative will provide academic and research institutions with much-needed help to transform their innovative technologies into actual products, and in partnership with key companies both global and local at that," said START managing director Adil M. Dhalla.

Besides START, other research institutes in the water industry ecosystem include Ngee Ann Polytechnic's Environmental and Water Technology Centre of Innovation (EWT-COI), which tackles membrane and water-related challenges such as biological and advanced engineering techniques for water purification. EWT-COI partners strategic industry sectors in applied research and development (R&D) and consultancy projects to turn ideas into practical solutions and innovations for a sustainable environment.

In particular, EWT-COI is unique in its focus on helping local small and medium enterprises (SMEs) to break into the water industry. For example, in 2014, EWT-COI conceptualised and developed a membrane-based evaporative cooler (MEC) that uses 20 to 40 per cent less water than a conventional industrial cooling tower and occupies a fraction of the space (Fig. 1). Relic Services, a local SME, took up the challenge of scaling up the 10 Refrigeration-Ton (RT) laboratory prototype for a test-bedding site in Yishun. The pilot MEC system is expected to be commercially operational by March 2018 and have a capacity of 50 RT.

Another aspect of Singapore's research ecosystem is its corporate R&D facilities. The GE Singapore Water Technology Centre, launched in 2009 by General Electric (GE) and housed at the National University of Singapore, focuses on developing ground-breaking technologies. The Centre enables GE scientists and engineers to explore areas such as pressure-driven and electro-separation membrane technologies, membrane chemicals and advanced analytical technologies. The solutions developed from this partnership benefit both GE's global clients and Singapore.

With these facilities helping to reinforce and leverage links between academia and industry in Singapore's water sector, the nation will continue to make waves in the field as a global thought leader. Singapore is already a Living Laboratory where companies can test-bed promising research ideas on a small scale and pilot solutions in real, operational settings. With the clear goal and vision of a vibrant eco-system teeming with start-ups, translation facilities and research institutes, PUB will continue to work with its partners to harvest research ideas and accelerate their development and commercialisation before exporting them to the industry and eventually the world.

Intelligent Watershed Management

The Intelligent Watershed Management programme aims to leverage developments in instrumentation, controls and information technology for hydrological, hydraulic, water quality and ecological research.

Using their expert knowledge and model simulations, water researchers can forecast future events and plan efficient countermeasures, thereby enhancing Singapore's capability in managing its catchments and reservoirs.

Using macrophytes to restore reservoir systems

Restoring turbid reservoirs into clear water bodies by selecting effective macrophytes

Fig. 1: *Ludwigia adscendens* (A) and *Persicaria barbata* (B) from the small mesocosm experiments

Freshwater ecosystems can exist in various stable states which are driven by different mechanisms. In reservoir management, one model of interest is the lake states model, where reservoirs exist in either a turbid state dominated by phytoplankton or a clear-water state dominated by macrophytes (aquatic plants). If the switching mechanism is known, turbid reservoirs can be restored to their clear-water state.

A team from the National University of Singapore, led by Darren Yeo and Hugh Tan in partnership with Simon Mitrovic from the University of Technology Sydney, is carrying out a two-year research project at Pandan Reservoir to investigate the macrophyte densities and coverage that can restore reservoirs from a phytoplankton-dominated state to a macrophyte-dominated one.

The study looks at how light, nutrients and allelopathy (the natural chemical inhibition of one plant by another) can influence the effective macrophyte densities and coverage that are required to effect such a change.

A series of small (100-litre) and medium (1,000-litre) mesocosm experiments were conducted with various species and combinations of macrophytes to identify which ones inhibit phytoplankton most effectively. The densities and area of coverage of the selected plants are then varied to determine the optimal growth parameters to reduce phytoplankton growth.

"Identifying the potential species to trial was challenging because we had to consider additional criteria such as local availability of the plants, their growth rate and the ease of maintenance," said Tan.

"Another challenge is to identify macrophytes that are effective at nutrient uptake or have allelopathic properties, or both, and could trigger a switch away from phytoplankton dominance while also being non-invasive and less weedy," Yeo added.

The small mesocosm experiments demonstrated that, at the highest density tested, two emergent plant species – *Ludwigia adscendens* (water banana) and *Persicaria barbata* (knot grass) (Fig. 1) – were effective in reducing total nitrogen concentrations by 20 – 24 per cent and phytoplankton biomass by 73 – 91 per cent compared to the controls.

In the next phase of the project where seasonal (monsoonal) variations will be captured, a submergent species will be tested in addition to the emergent species in medium and large (10,000-litre) mesocosm experiments in Pandan Reservoir.

Where applicable, allelochemicals produced by both the macrophytes and cyanobacteria will also be analysed to determine allelopathy's role in restoring the water quality of Singapore's reservoirs.

"The results from this study will give reservoir managers the information required to develop and sustain macrophyte communities that are effective in maintaining local reservoirs in a clear-water state," said Mitrovic. "This will reduce the negative impact of cyanobacterial blooms, which are aesthetically unpleasant and costly for water treatment."

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Increasing the efficiency of operational biomonitoring through subsampling

Subsampling methods could improve sample processing efficiency without impacting the integrity of long-term biomonitoring datasets

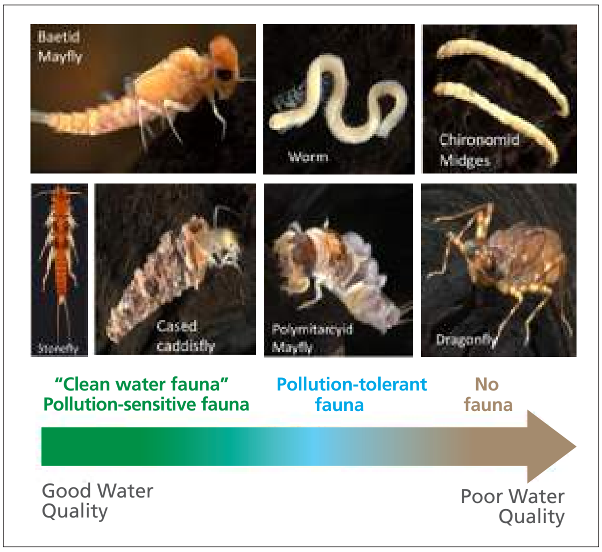

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Fig. 1: The presence of benthic (bottom-dwelling) macroinvertebrates, weighted by their sensitivity to pollution, is used to calculate biotic indices of water quality and ecological health

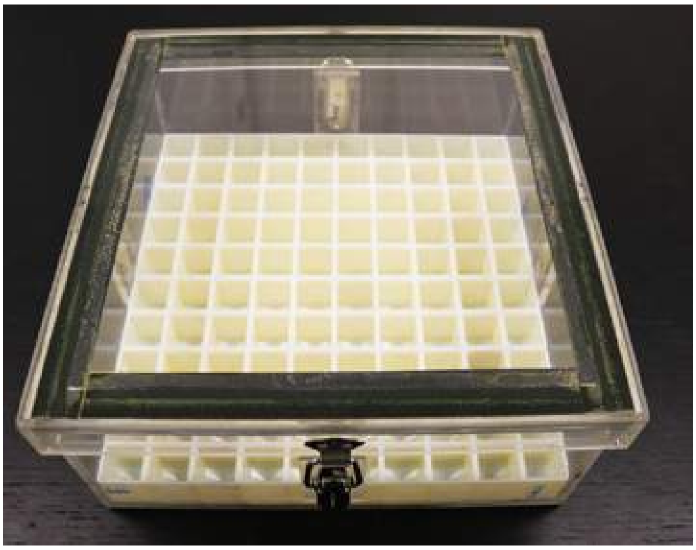

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Fig. 2: A view of the modified Marchant box consisting of an external clear acrylic box and 100 3D-printed cells

The presence or absence of certain aquatic organisms in freshwater systems is an indication of the ecological quality of the water, and can shed light on specific pollution issues or "stressors" on the ecosystem (Fig. 1). The monitoring of these indicators, which is known as biomonitoring, can integrate inherently noisy environmental data in a cohesive manner to directly address issues of interest, such as urban-runoff and nutrient enrichment.

The environmental and ecological information obtained from biomonitoring can be combined to form a single indicator score on a scale with classes of "poor" and "good" ecological quality to track and benchmark the ecological status of the freshwater body. Through PUB-funded projects, Esther Clews and her team from the National University of Singapore developed two indices (SingScore and BQI_{SING}) for freshwater systems in Singapore. These are designed to capture ecological aspects relevant to conditions in Singapore, and have been assessed for reliability in a range of natural, modified and transitional environments, including streams within nature reserves, drainage canals and "naturalised" environments such as the Kallang River in Bishan-Ang Mo Kio Park.

Historically, the application of biomonitoring is a tedious process involving a long sample turnaround time. Clews and her team thus undertook a project to increase the efficiency of operational biomonitoring through subsampling. After reviewing numerous subsampling strategies used internationally, the team designed a modified Marchant box where samples are partitioned into 100 smaller cells, and constructed it using 3D printing technology (Fig. 2). The modified box can be used to process a subsample of the full sample collected, by selecting only a subset of cells from the box for processing. This facilitates even faster processing since the amount of sample to be processed is reduced, and each of the box's cells can be removed separately, eliminating the need to manually extract macroinvertebrates from each cell using a pipette and tweezers.

However, to ensure that the integrity of the long-term biomonitoring dataset is not compromised by processing a fraction of the sample, an appropriate subsampling cut-off level that will yield the same indicator score as the fully-processed sample needs to be determined. Dr Clews and her team used different numbers of cells from the modified Marchant box, and different counts of specimens, to conduct a cost-benefit analysis of the precision and accuracy of data that resulted from these different subsampling levels. The results indicated that subsampling using the modified Marchant box is feasible and can reduce sample processing time by as much as 50 per cent.

The results from the team's study could enable PUB to streamline its biomonitoring operations and free up manpower to perform other critical tasks.

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Modelling reservoir water quality under the effects of climate change

Looking at reservoir water quality under different climatological and socio-economic projections

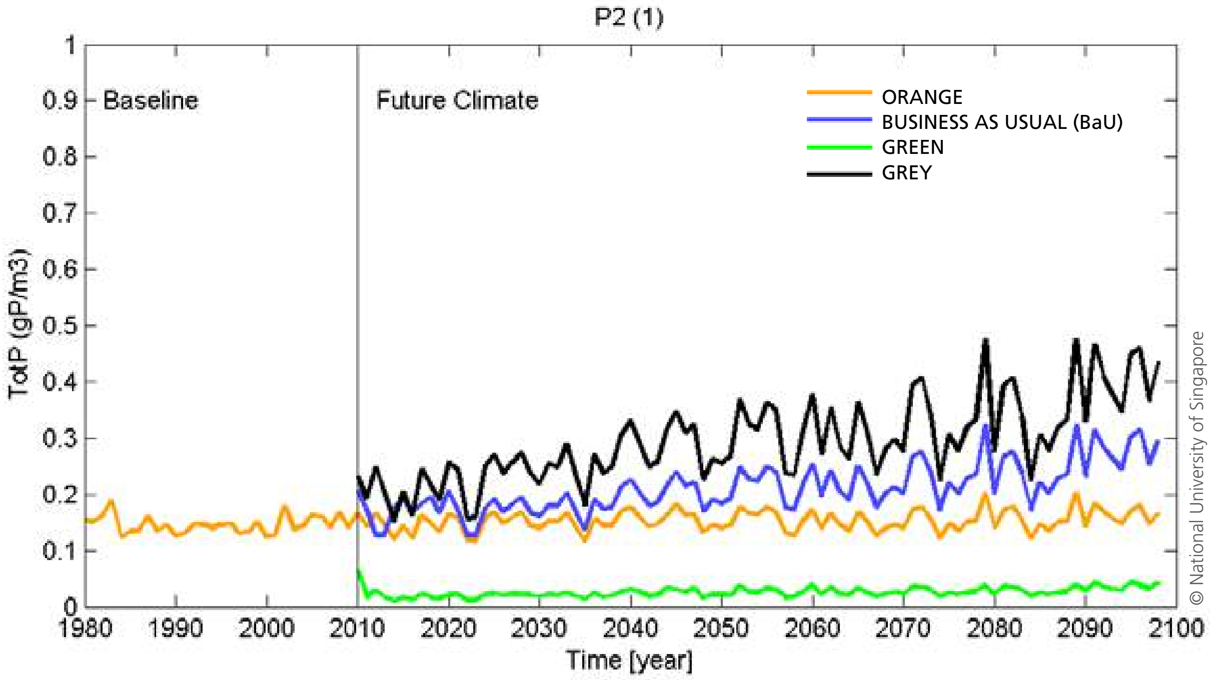

Fig. 1: Projected changes in total phosphorus concentration at a station in Punggol Reservoir. The chart shows the impact of climate change alone (Orange), compared to that of climate change and socio-economic developments under three scenarios: Business as Usual (BaU), limited sustainable development measures (Grey) and full-scale measures (Green)

Once considered a matter to be addressed in the distant future, climate change is now an increasingly important factor in planning for the future. The impact of climate change can be exponentially higher and affect more lives and infrastructure, when coupled with population growth, socio-economic developments and intensified land use. As such, society needs to adapt to climate change.

With this in mind, a team led by Vladan Babovic from the National University of Singapore worked with Dutch applied research institute Deltares to understand how the water quality of Singapore's freshwater reservoirs could change over the next 100 years as a result of climate and socio-economic changes. Adaptation measures and water management practices needed to cope with these changes were also explored.

The researchers investigated the effect of climate change on reservoir water quality in the Marina and Punggol-Serangoon catchment areas. They also identified trends of key climatological variables and gathered data on anticipated changes across a range of water quality indicators. The study utilised the Centre for Climate Research Singapore's projections for temperature, precipitation and surface and lower tropospheric winds. These used Global Circulation Models (GCMs) that were downsized to Singapore's scale. To simulate future rainfall-runoff relationships and flow dynamics, hourly rainfall time series from GCMs and other meteorological forcing variables were fitted into an integrated modelling framework that was based on a distributed hydrologic model coupled with flow models.

The simulation scenarios took into consideration a range of factors such as population growth, present and future land use and runoff management practices. A separate emissions module was used to develop pollutographs and determine spatio-temporally resolved pollution flowing into reservoirs under several climate and socio-economic scenarios. By integrating these inputs into a water quality model, key water quality indicators in reservoirs were simulated, such as the concentrations of total nitrogen (TN), total phosphorus (TP), total organic carbon (TOC) and suspended solids (SS).

Fig. 1 illustrates the projected change in TP concentration in Punggol Reservoir over a 90-year simulation period. Under the Grey scenario (limited sustainable development measures implemented), TP increases steadily throughout the 90-year period. In contrast, the Green scenario (full-scale implementation of sustainable development measures) achieved the lowest TP concentration after 90 years. The study concludes that climate change alone yields no significant impact on the change of water quality and showed that the greatest effects upon water quality parameters could be attributed to future socio-economic activities and associated pollution emission scenarios.

The team hopes to use the gathered data and results to provide insights for reservoir management strategies and encourage action to safeguard Singapore's water resources in the face of climate change.

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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 more than 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.

Reducing fouling of ultrafiltration membranes

Using high-tensile hydrophilic membranes and nano-bubble induced chemical cleaning to increase Clean-in-Place efficiency and reduce membrane fouling

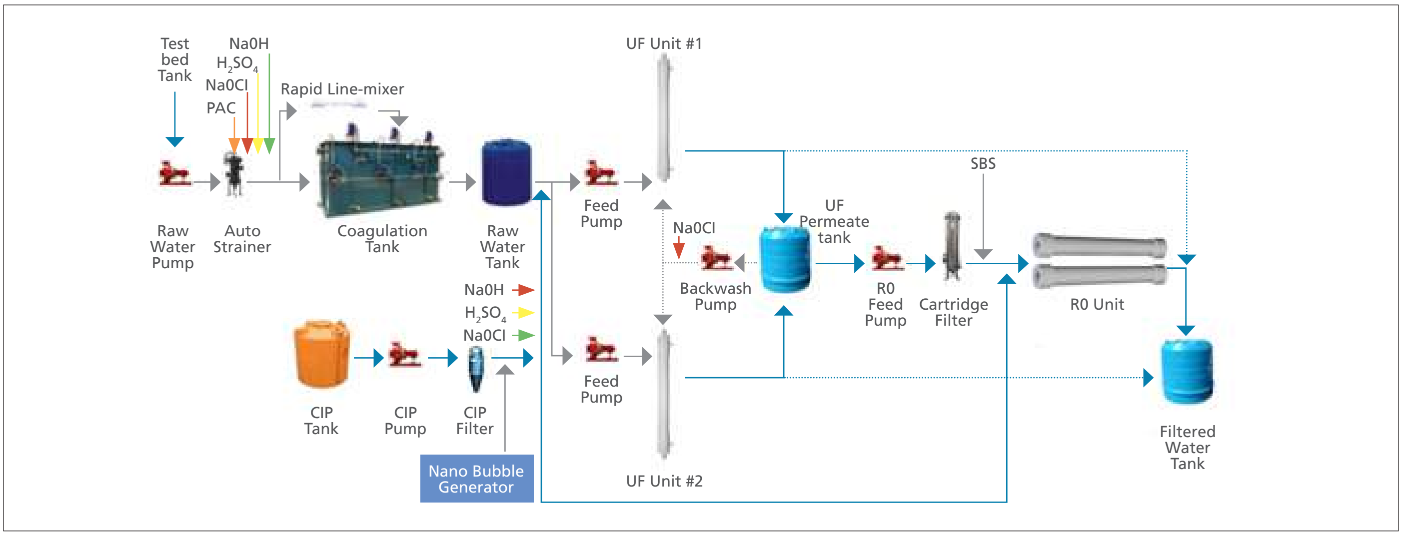

Fig. 1: Schematic diagram of the "Less Fouling and Enhanced Cleaning" membrane system

Fouling of ultrafiltration (UF) membranes in water treatment, used water treatment and pre-treatment for desalination is a problem faced by plant operators as it compromises the membranes' performance and increases operating costs. While regular chemical cleaning – a process known as Clean-In-Place (CIP) – is used to mitigate fouling, CIP results in downtime and decreased output, and usually becomes less effective over time.

To reduce fouling and the frequency of CIP, Hyosung developed a "Less Fouling and Enhanced Cleaning" (LFEC) membrane system (Fig. 1). It comprises a high-tensile hydrophilic UF membrane made of acetylated methyl cellulose (AMC) as well as equipment that generates nano-bubbles in the chemical cleaning solution for more effective membrane cleaning.

The AMC polymer has a molecular weight of more than 300 kilodaltons (kDa) – about thrice that of conventional hydrophilic membrane materials (Fig. 2). The polymer's high tensile strength allowed Hyosung to further develop it into a hollow fibre membrane, producing a hydrophilic membrane of equal or even higher tensile strength than conventional polyvinylidene fluoride (PVDF) membranes. PVDF membranes are known for their material toughness, but are prone to fouling due to their hydrophobicity. The AMC membrane has been shown to possess excellent anti-fouling properties compared to PVDF ones.

"Resistance to membrane fouling is important to reduce energy consumption in the treatment process. In addition, less chemicals will be required for membrane cleaning, which will improve the stability of operations and lessen the environmental impact of the cleaning process," said Lim Seong Han, general manager of Hyosung Research, Development and Business Labs.

Another feature of the LFEC membrane system is its use of nano-bubble induced chemical cleaning. During this process, bubbles that are several micrometres in size are generated in solution, but subsequently shrink to about 10 nanometres each due to their relatively high internal pressure. Unlike larger bubbles, nano-bubbles do not rise readily to the water surface (and thereafter burst). Instead, they remain within the water for a period of time, accumulating at and adhering to contaminants at nucleation sites before collapsing, thus facilitating the flocculation and removal of the contaminants. As a result of the vibration and heat generated during the collapsing process, hydroxyl radicals are also released into the water, further reducing membrane fouling by microbes.

A pilot test conducted at the water treatment facilities of the Hyosung Anyang Sewage Plant in South Korea showed that nano-bubbles significantly improved the efficiency of CIP without a corresponding increase in energy consumption. Hyosung is also test-bedding the LFEC membrane system in a desalination pre-treatment pilot trial at PUB's research and development facility in Tuas, where it will be compared to the performance of a conventional PVDF UF membrane system and the CIP processes used by PUB.

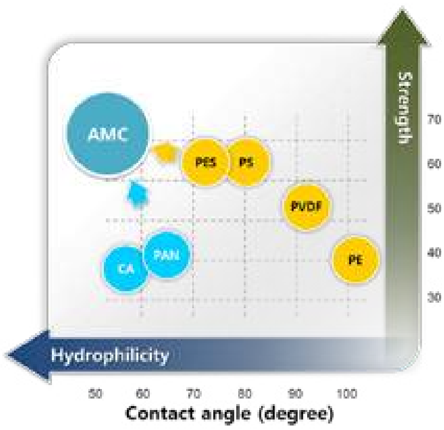

Fig. 2: Graph comparing various membrane types' hydrophilicity and tensile strength

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Saving energy through nanofiltration

High-performance nanofiltration hollow fibre membranes and modules improve pre-treatment of feed water

Fig. 1: The cross-section of a 1-inch nanofiltration (NF) hollow fibre module

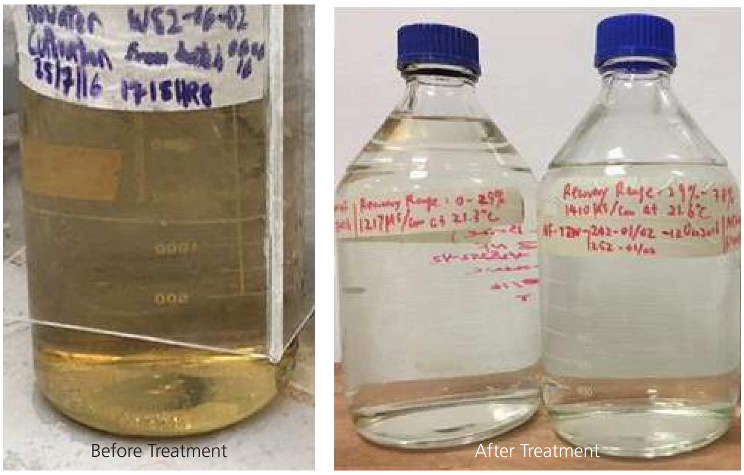

Fig. 2: NF hollow fibre membranes were used in a laboratory-scale treatment of reverse osmosis retentate in NEWater production. The results showed a clear difference in colour between the untreated and treated samples

Singapore has limited space for rainwater collection and storage. To overcome this limitation, the country supplements its water supply with water from other sources, including desalinated water and NEWater, which are produced from seawater and treated used water respectively.

Desalination and NEWater production in Singapore consume more energy compared to conventional water treatment methods, and involve reverse osmosis (RO), where seawater or domestic treated used water is subjected to high pressure and pushed through ultra-fine membranes to remove dissolved salts, minerals and organic solutes. While RO is highly effective, its membranes tend to foul and degrade in performance over time due to particles in the feed water depositing on the membrane surface. Large amounts of particles can exist in the feed water if the pre-treatment process was inadequate.

To address this problem, Neal Chung Tai-Shung from the National University of Singapore (NUS), working with researchers at MICRODYN-NADIR Singapore (MNSG) and NUS, designed a new nanofiltration (NF) hollow fibre membrane specifically for the pre-treatment of RO feed water. This membrane, which has smaller pores compared to those of ultrafiltration membranes used in conventional pre-treatment, offers better separation potential and is relatively resistant to fouling. It is effective at lower transmembrane pressures without compromising on flux, and its hollow fibre configuration allows it to be cleaned more easily compared to the flat sheet form, improving its durability.

The researchers' invention can be used to remove more particles from RO feed water during its pre-treatment, reducing the need for RO membrane cleaning and replacement. This will improve RO's productivity and lower its energy consumption.

The NF hollow fibre membrane was developed from polyethersulfone (PES) (Fig. 1), a chemically stable material. The researchers produced an outer-selective NF membrane with a pore size of less than 1 nanometre and a water flux of 15 litres per square metre per hour per bar (LMH/bar), exceeding their initial targets as high water flux is typically achieved at the expense of small pore size or vice versa. In the next stage of the project, the NF hollow fibres will be incorporated into a 10-inch module so that their performance in desalination and NEWater applications can be examined in a pilot scale setup by MNSG at a PUB site.

"This high-performance NF hollow fibre membrane could effectively mitigate one of the most persistent and costly challenges faced in RO," said Chung.

The NF hollow fibres could also be used to treat RO retentate to reduce its total organic carbon (TOC) content (Fig. 2). RO retentate with less TOC is less likely to foul, making it more suitable for electrodialysis reversal for further water recovery, or pressure retarded osmosis for power generation.

This research grant is supported by the Singapore National Research Foundation under its Environment & Water Research Programme and is administered by PUB, Singapore's National Water Agency.

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Molecular design and synthesis of recombinant aquaporins for biomimetic membranes

Engineering designer water channels with enhanced water flux

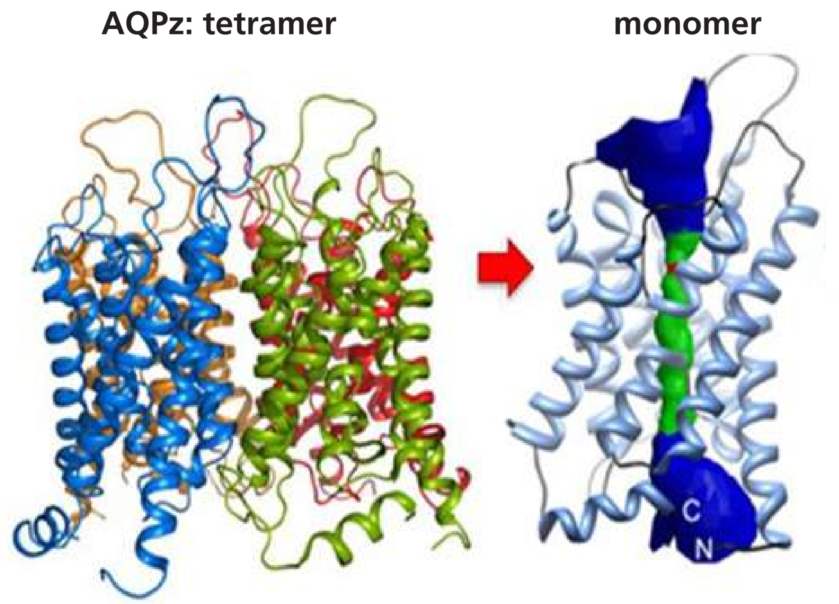

Fig. 1: The molecular models of a tetrameric aquaporin-Z (AQPz) (left) and a genetically engineered monomeric AQPz (right)

The growing demand for clean water calls for new water purification methods that can supply high quality water in a sustainable and cost-efficient way. A team of researchers from the National University of Singapore Environmental Research Institute (NERI), comprising Kandiah Jeyaseelan, Tong Yen Wah and Arun Armugam, delved into nature's workings and sought inspiration from one of the fundamental molecules that sustain life: aquaporins. These transmembrane proteins, which are found in living organisms, regulate the transport of water molecules in a highly selective manner, essentially functioning as nature's filtration system.

The incorporation of aquaporins into filtration membranes, otherwise known as biomimetic membrane fabrication, is a rapidly developing field in the water industry. Each aquaporin subunit is highly permeable to water and allows only water molecules to pass through at a rate of 3 x 109 molecules per second, making it ideal for water filtration purposes. The NERI team focused on an aquaporin called aquaporin-Z (AQPz), which is derived from the bacterium *Escherichia coli*, due to its additional advantages: it requires low Arrhenius activation energy and rejects more salt, ions and small molecules than other known plant and animal aquaporins. Applications of naturally occurring AQPz have been limited by the molecules' tendency to aggregate during the membrane fabrication process. The aggregation of AQPz, which arises from the molecule's tetrameric configuration, has resulted in biomimetic membranes with greatly reduced water flux. To overcome this problem, the NERI team produced genetically engineered monomeric AQPz mutants that are each about 80% smaller than the parent molecule (Fig. 1) and will be less likely to aggregate. After validating the success of this approach, the team cloned a different aquaporin (AQUAT) from a thermophilic bacterium. These aquaporins have a much higher water flux (8- to 10-fold higher) than the native AQPz tetramer as they are relatively small in size and do not form aggregates. Moreover, these aquaporins can be incorporated into biomimetic membranes at higher densities, further enhancing the membranes' performance.

The researchers are working to scale up aquaporin production for industrial use, and exploring ways to further reduce the aquaporins to just their pore regions without compromising their functional properties to increase the efficiency of the membrane. Collaborations with overseas partners are also underway to investigate methods of modifying the molecular architecture of the synthetic aquaporins to obtain water pores that are smaller and more stable.

Inspired by nature and improved by engineering expertise, these novel aquaporins may be key to developing a new generation of enhanced biomimetic membranes for water purification.

This research grant is supported by the Singapore National Research Foundation under its Environment & Water Research Programme and is administered by PUB, Singapore's National Water Agency.

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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 to consumers 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 even greater technological innovation.

Using bacteria to monitor used water quality

A novel bioelectrochemical approach to detect Volatile Organic Compounds in sewers

Fig. 1: The genetic engineering of *Escherichia coli*

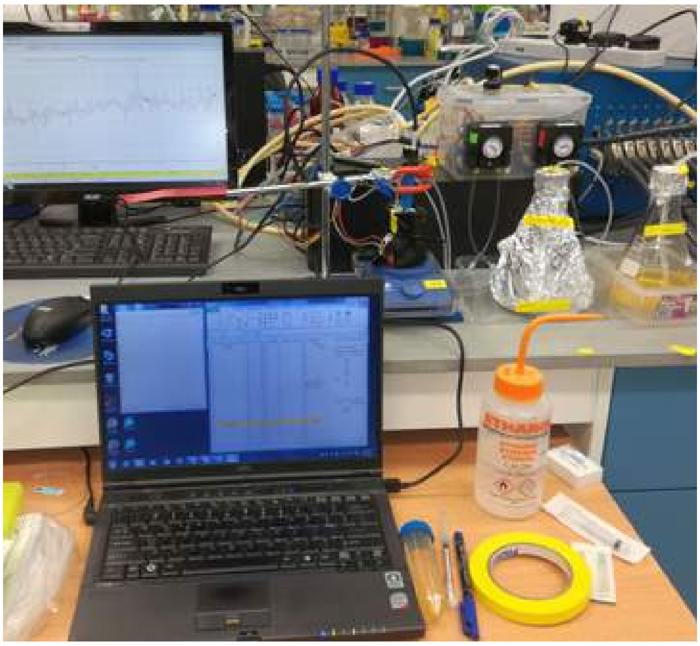

Fig. 2: The laboratory assembly of the novel bioelectrochemical sensor

Volatile organic compounds (VOCs) such as benzene, toluene and phenols are commonly used in the electronics and textile industries. While industries manage and treat their trade effluent before discharging it into the sewers, some VOCs may still be found in the effluent occasionally due to illegal discharge. The presence of VOCs in used water is a threat to used water treatment plants, as some VOCs are toxic to microorganisms and could impede the biological treatment process in used water treatment. Current methods for detecting VOCs in used water, however, often require offline analysis and hence cannot provide operators with real-time information for timely action.

Enrico Marsili and his team from the Singapore Centre for Environmental Life Sciences Engineering at Nanyang Technological University have developed a novel bioelectrochemical approach that uses genetically engineered bacteria to detect specific VOCs in the sewer network. As these VOCs are toxic to the bacteria, their presence will affect the bacteria's metabolic rate, leading to variations in the current produced and electrochemical signals measured when compared to a baseline. This approach can provide close to real-time information on the presence of VOCs in samples.

The team modified *Escherichia coli (E. coli)*, an organism with readily available genetic information, to respond to the targeted VOCs. Since VOCs can cause unique transcriptomic signals in *E. coli*, the scientists decided to use *E. coli* gene regulatory elements that are responsive to specific VOCs as the sensory component in their biosensor. To achieve this, the team analysed *E. coli* grown in the presence of the selected VOCs, identified possible candidate gene regulatory elements and tested them for their responses to the types and doses of VOCs present. The team then genetically modified the suitable candidates to include an electroactive bioreporter, and evaluated their response to VOCs using electrochemical measurements (Fig. 1).

Preliminary results from the study showed that the *E. coli* genes respond differently when exposed to different VOCs. A total of 625 genes were found to be responsive to at least four of the VOCs tested in the study. Various functional gene categories were also differentially expressed when compared to the control category. The team is using this information on the differentially regulated genes and their regulatory elements to design a new bioreporter strain.

The scientists are also developing a small bioreactor in a laboratory prototype (Fig. 2) to house the *E. coli* culture and the instruments necessary to detect the electrochemical signals.

While more work needs to be done, the devices could potentially be deployed in factories and specific manholes along the sewer network, to quickly alert PUB to targeted VOCs in the used water that could affect the used water treatment process downstream.

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Shower smart

The effect of real-time information on water usage in showers

Fig. 1: A smart meter is installed on the showerhead to track water usage

Fig. 2: Deploying smart meters in the households

Water is a precious resource and managing both supply and water demand is important to ensure water sustainability. To this end, the national objective is to reduce Singapore's water usage per person from 148 litres in 2016 to 140 litres per day by 2030.

As showers account for 29 per cent of a household's monthly water consumption, Sing Tien Foo and his team from the National University of Singapore and three other overseas universities embarked on a study with PUB to explore the effectiveness of behavioural interventions in reducing water usage in showers.

Inspired by a previous experiment conducted in Switzerland, 550 residential households in Singapore were fitted with smart shower devices (Fig. 1) that recorded their water usage data automatically over four to six months (Fig. 2). Through the data collected from a total of 300,000 showers, the researchers found that Singaporeans used an average of 20 litres of water for a five-minute shower.

The researchers also randomly divided these households into five groups and gave each group a different water consumption target to achieve per shower. The targets ranged from 10 to 35 litres, corresponding to ambitious, moderate or easy goals. During showers, the smart shower device displayed in real-time the volume of water that had been used, as well as an indication of "Very Good", "OK" or "Too Much", depending on the water consumption goal that had been set and the amount of water used thus far.

The researchers concluded through the study that the households' water consumption was reduced by almost 10 per cent per shower when they received feedback from the smart meters. This corresponded to 2.1 litres of water saved per shower. The researchers also found that the goal set for the household played a crucial role. To best motivate households to use less water during showers, the goal must be neither too ambitious (less than 10 litres per shower) nor too lenient (30 litres or more). In the study, the most effective goal was 15 litres, and households with this goal saved up to 3.8 litres, or 19.9 per cent, of water per shower. This is equivalent to about 5 litres of water saved per capita on a daily basis, given that a person takes 1.3 showers on average per day in Singapore.

The key difference between the smart shower device, when compared to alternative methods of providing water consumption information to users, was that it gave real-time information to users while they were using water, the researchers said. Such provision of real-time information, when used in conjunction with an appropriate goal, could nudge households to use less water during showers and effectively complement water conservation policies.

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An automated aerial device for monitoring underground tunnels

Unmanned aerial vehicles to inspect Singapore's Deep Tunnel Sewerage System

Fig. 1: A miniature unmanned aerial vehicle (UAV) for use in inspecting the Deep Tunnel Sewerage System

Fig. 2: A flying UAV next to a pipe segment

Singapore's Deep Tunnel Sewerage System (DTSS) is a superhighway for the management of used water, and regular inspections and maintenance of the protection lining inside the deep tunnel sewers are key to preventing disruptions to its operations. However, the depth of the tunnel makes it challenging for human entry to conduct manual inspections.

AeroLion Technologies (ALT) has proposed a novel way to carry out inspections. They plan to automate a miniature unmanned aerial vehicle (UAV) system to capture high-resolution images of the tunnel's internal wall (Fig. 1 and Fig. 2). The UAV system, which will fly in and out of the tunnel via manholes and drop shafts, will avoid contact with the flowing used water and its drag force.

Today, even with an advanced understanding of Global Positioning System (GPS)-based UAV technology, enabling a miniature aerial machine to fly into an underground tunnel without a GPS signal is still extremely challenging. In addition, the UAV has to be able to operate in darkness and high humidity within the tunnel, over long distances and in the presence of hazardous gases.

ALT has specially designed an aerial platform to overcome these challenges. Its in-house UAV GPS-less navigation algorithm uses depth cameras instead of pure range sensors or image sensors. Such cameras are better suited to record both colour and distance information for every pixel captured, as the structural similarity of the DTSS interior renders range sensors incapable of estimating the forward velocity or position of the UAV in the DTSS, while image sensors are unable to provide depth information in their two-dimensional images.

The UAV's flight inside the tunnel will be fully automated so that it can complete its inspection even if it loses communication with ground control. It will have a ring of depth cameras with active illumination to avoid dead-spots. In addition, a set of sensors with sonar and/or laser rangefinders will be mounted on the UAV to detect the water and silt level in the tunnel to compensate for the lack of vision-based navigation.

After each flight, the image data collected by the UAV will be processed to reconstruct an internal map of the tunnel so that potential defects can be identified.

The first phase of this project started in August 2016. It includes a flight demonstration at an offset shaft of the DTSS to verify the UAV's autonomous tunnel flight capability as well as the quality of the data collected.

In the second phase, the UAV's design will be optimised to maximise its entrance-to-exit flight endurance and improve its safety features. If the project is successful, the UAV technology will be a valuable tool for DTSS inspection and maintenance work.

This research grant is supported by the Singapore National Research Foundation under its Environment & Water Research Programme and is administered by PUB, Singapore's National Water Agency.

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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.

Increasing the energy efficiency of membrane bioreactor operations

Demonstrating a novel fouling control method for membranes

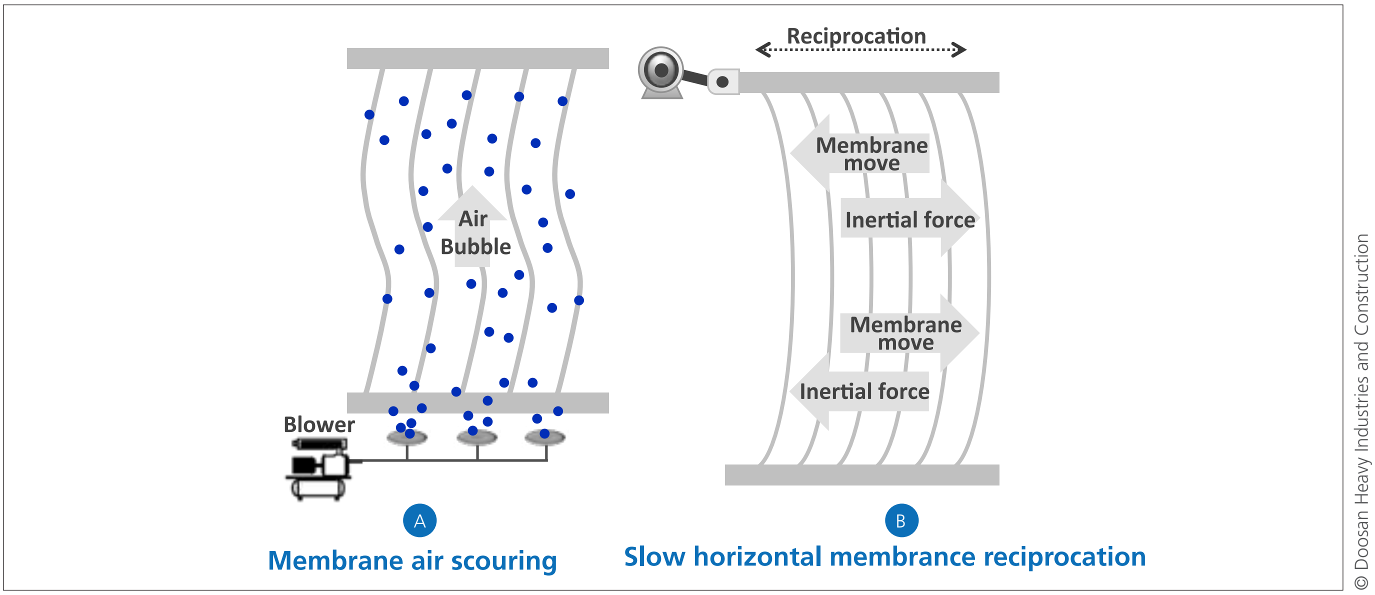

Fig. 1: Diagram showing the membranes of a conventional membrane bioreactor (MBR) system (A) and the Low Energy No Aeration (LENA) MBR system (B)

Over the past two decades, membrane bioreactor (MBR) systems have paved the way for numerous advancements in used water treatment. The MBR system replaces the need for aeration basins and sedimentation tanks by combining a microfiltration or ultrafiltration membrane process with a suspended growth bioreactor. Using this system, the effluent produced is of high enough quality to be discharged or further treated for various uses. It also does not occupy much space, making it ideal for land-scarce Singapore. However, this process consumes considerable energy.

Specifically, the air blowers, which prevent membrane bio-fouling, require much more electricity than conventional used water treatment systems and contribute to the majority of their operating cost. To reduce energy consumption and thus enable future large-scale application, Doosan developed an innovative technology called the Low Energy No Aeration (LENA) MBR system.

The LENA MBR system replaces membrane air scouring with mechanical membrane reciprocation (Fig. 1), which uses less energy. The latter creates an inertial force that acts on membrane fibres to propel foulants from the membrane surface. These fibres are also able to move relative to one another during reciprocation due to their loose packing, preventing sludge from getting clogged in the fibre bundle.
To evaluate the performance of this technology under local conditions, Doosan test-bedded a 1,600 cubic metres per day demonstration plant at the Ulu Pandan Water Reclamation Plant (Fig. 2). Mixed liquor suspended solids were drawn from an existing aeration basin as the feed. The system consisted of two 20-feet containers which housed a membrane tank and functioned as an operation control room respectively. The system's operation was automated and controlled by a programmable logic controller based on a complex control philosophy for automated remote operation and data acquisition.
To compare the performance of the LENA membrane reciprocation process with that of a conventional membrane air scouring process, the researchers recorded both systems' energy use and the amount of filtrate that they produced each day. The LENA process used 0.003 to 0.015 kilowatt hour per cubic metre (kWh/m^3) of filtrate, compared to conventional air scouring's 0.1 to 0.15 kWh/m^3 – substantial savings of more than 85 per cent.

Fig. 2: Installation of the LENA MBR pilot plant

"Our collaboration with PUB shows that the LENA MBR system can significantly reduce the energy consumption for MBR operations while achieving similar or better membrane performance when compared to conventional MBR systems with air scouring," noted Roh Hyung Keun, who is leading the work at Doosan. If successful, this technology could provide a prospective solution to the energy problem for the used water industry.

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Maximising biogas recovery for used water treatment

High-performance membranes to optimise biogas recovery

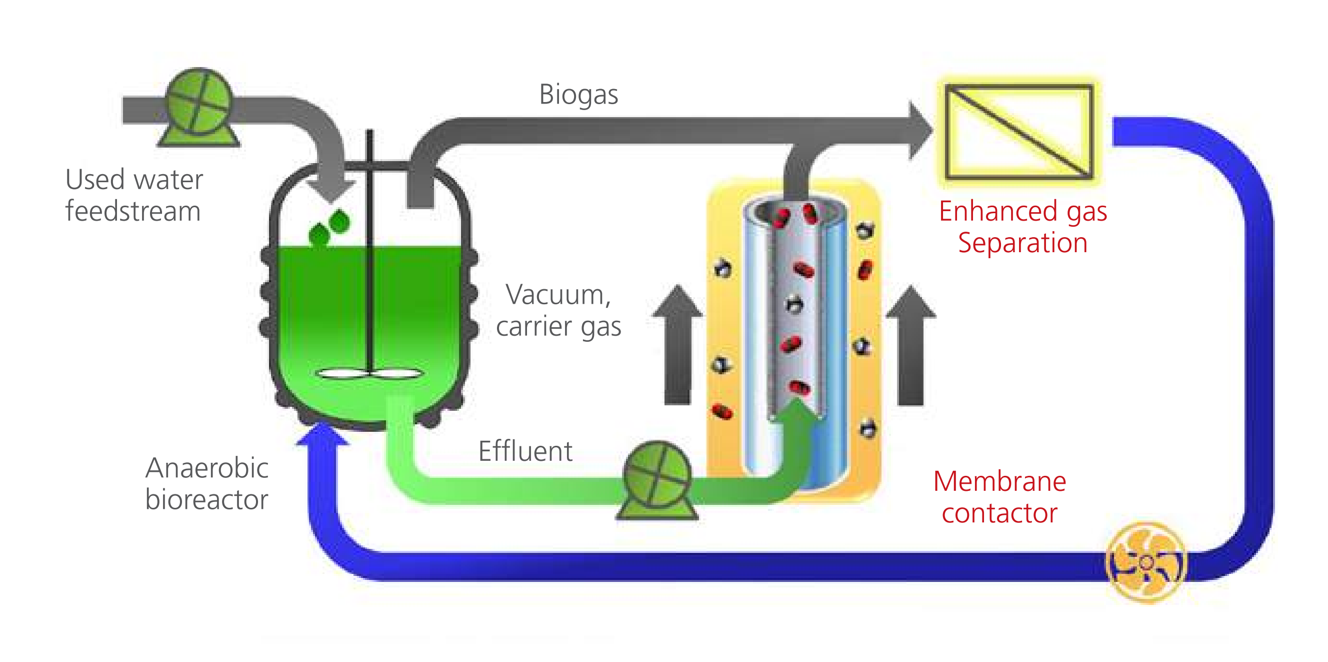

Fig. 1: A schematic of the process to maximise methane gas recovery from effluent produced by an anaerobic bioreactor

Anaerobic processes are a promising alternative method to treat used water compared to the conventional activated sludge process. They use less energy as they do not require aeration, which consumes considerable electricity. Biogas containing methane, which is an energy source, can also be extracted from the gases in anaerobic bioreactors and from the effluent produced by these bioreactors and other anaerobic processes.

Current efforts to recover more energy from anaerobic processes, however, are focused only on the gas phase, although there are also significant amounts of dissolved biogas and methane in anaerobic bioreactors' effluent. As such, a team from the Singapore Membrane Technology Centre (SMTC) at the Nanyang Environment and Water Research Institute is exploring membrane-based separation methods to better extract dissolved biogas from the effluent.

Specifically, the researchers are evaluating the use of a membrane contactor which houses hollow fibre membranes. As the effluent passes through these membranes, biogas is extracted and permeates to the other side of the membranes (Fig. 1). Wang Rong, the team's co-principal investigator, said that such methods are cost-effective and have low energy intensity.

A laboratory-scale setup was able to recover about 9 to 12 grams of methane gas per square metre of membrane. Simulations also showed that it could be possible to recover more than 35 per cent by volume of methane gas from the effluent. This would give a positive net electricity outcome of 0.11 mega joules per cubic metre of effluent.

One drawback of the membrane contactor, however, is that it also desorbs carbon dioxide from the effluent. While this is not a key concern for water reclamation plant operators, further separation of the extracted gases is necessary for applications that require biogas of a quality close to that of natural gas.

The SMTC team thus incorporated another membrane-based step downstream to remove carbon dioxide from the combined stream of extracted biogas. The results showed that, for this gas separation step, the use of nanomaterials to create composite membranes can increase the methane recovery rate from the combined biogas.

While the study is still underway, the researchers are hopeful of its potential. "Our strategy to maximise the amount of recovered methane gas, by extracting biogas dissolved in the effluent and enhancing the downstream gas separation process, can bring us one step closer to PUB's vision of energy self-sufficient water reclamation plants," said principal investigator Bae Tae-Hyun.

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Towards energy-neutral used water treatment plants

Developing an efficient, stable and sustainable used water treatment process for energy-neutral treatment plants

Fig. 1: The Efficient AB pilot plant at the Kranji Water Reclamation Plant

Fig. 2: A laboratory analysis of the biogas methane potential of the sludge produced

As Singapore's population grows, the volume of used water to be treated, and hence the cost of operating used water treatment plants, will also increase. To address this challenge, PUB and SUEZ are developing an innovative and sustainable technology called the Efficient AB (E-AB) process.

This process comprises two stages. The first A-stage involves a well-established biosorption technology that enables the early capture of carbon-rich organics from raw used water, so that more biogas can be produced from the A-stage sludge that is sent to anaerobic digesters. With more biogas, more energy can be generated to offset the energy consumption of the used water treatment process. This can potentially make the treatment process energy-neutral, which means that it would use no more energy than it generates.

The second B-stage removes nitrogen from used water through a nitrite-shunt process, which is a shortcut for the natural nitrogen cycle. The resultant effluent is of a higher quality and not only complies with effluent discharge limits but can also undergo tertiary treatment, such as Singapore's NEWater treatment process, for potential reuse.

As the E-AB process is a biological one, it has to be tested and optimised in laboratory and pilot-scale studies (Fig. 1 and 2). These studies show that the process can be successfully adapted for use with Singapore's used water and in the local climate. The piloting phase of the project focuses on developing advanced operational and control strategies to improve and stabilise the A-stage for maximal carbon capture and biogas production. It also optimises the energy efficiency of the B-stage process by reducing the aeration demand for ammonia removal.

In line with the development of smart solutions in Singapore and to enhance the operations of the E-AB process, the project team is collaborating with the Danish Hydraulic Institute on a smart approach to deploy this process in the pilot plant. This involves using smart technologies and sensors, as well as a smart dashboard that includes key performance indicators, to enhance process control and monitoring. The development of an influent prediction and modelling module based on real-time weather data acquisition is also in the works.

If this project is successful, it could reduce the energy required in used water treatment processes and recover more energy from carbon-rich sludge. To ensure that it is a sustainable and innovative solution that can be implemented in existing and future used water treatment plants, the project team is also exploring the use of more automation, remote controlling and monitoring that could reduce the plants' reliance on operators. In Singapore, the project's findings could prove invaluable in aiding the technical design of the future Tuas Water Reclamation Plant.

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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.

Raw water quality research programme at Van Kleef Centre

Targeting nutrient and algae control to improve raw water quality

Fig. 1: The Van Kleef Centre for freshwater research

The continued urbanisation of Singapore's catchments means that effective management of surface water quality and ecology – and maintaining the technical capability to do so – is of strategic importance to PUB.

The Van Kleef Centre (VKC) (Fig. 1), located along Sungei Ulu Pandan, carries out research on raw water quality to build PUB's expertise in the nutrient cycling and transport, reduction of nutrient loading, algae growth control and ecological management of raw water. The VKC houses a well-equipped laboratory for environmental sample analyses and has an outdoor work area comprising a bioflume, flow tanks, biosorption columns and a plant nursery for propagating plants for research.

PUB's Water Quality Management and Modelling Division has started a two-and-a-half-year research programme at the VKC to investigate nutrient and algae control methods. These methods will help to improve the aesthetics of Singapore's reservoirs and reduce the impact of algae growth on downstream water treatment processes and recreational reservoir users.

The programme's first experiment involves evaluating the effectiveness of commercially available filter media in removing nutrients. Filter media with large surface areas for microbial growth and high anion-exchange capacity can be used to lower the nutrient levels in water to reduce algae growth. The team will use a series of tank tests to shortlist cost-effective products for field trials before applying them on a larger scale.

In addition, tank experiments are being conducted to determine the relative nutrient uptake efficacies of various submerged and emergent macrophyte species (aquatic plants) (Fig. 2). The species tested either occur naturally in Singapore or are found in PUB's wetlands island-wide. The experiments also aim to improve the understanding of the effect of root volume on nutrient removal efficacy. The findings will help guide the selection of macrophyte species for future wetland projects and complement PUB's collaboration with the National University of Singapore on the use of macrophytes for reservoir restoration.

Other experiments with a similar focus on nutrient and algae control in waterways and reservoirs are in the pipeline. These studies include investigating the use of zooplankton as algae grazers to control algae growth, and finding correlations between sediment nutrient fluxes and internal nutrient loads under different environmental conditions. The researchers will also test the efficiency and cost effectiveness of combined aeration and fine-bubble mixing systems in improving dissolved oxygen levels and algae control, as well as design and test a new low-power algae scum removal system. These studies will eventually help to improve operations related to raw water quality in Singapore's waterways and reservoirs.

Fig. 2: Aquatic plants being tested for their ability to take up nutrients in water

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Rapidly detecting assimilable organic carbon

Bacterial strain improvement and fluorescence tagging could increase the efficiency of detecting assimilable organic carbon in water

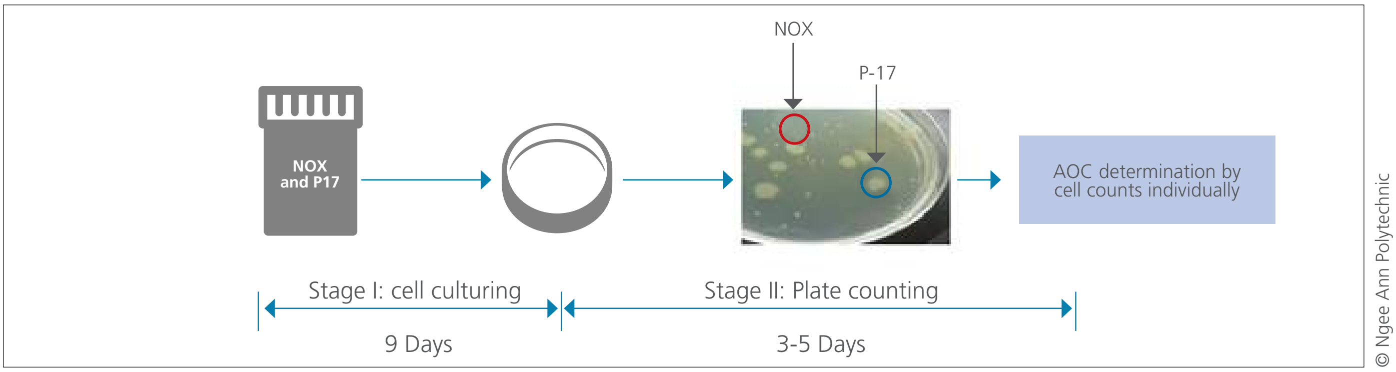

Fig. 1: Conventional assimilable organic carbon (AOC) detection process

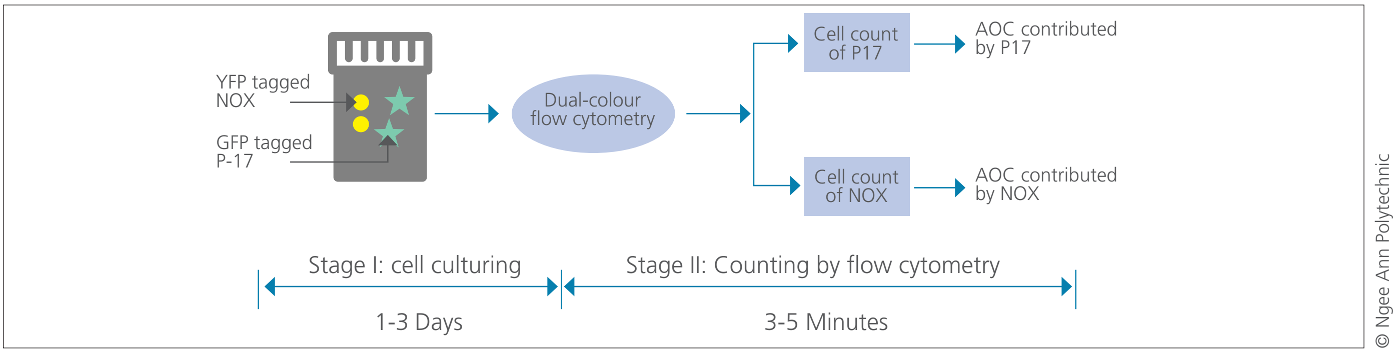

Fig. 2: New AOC detection process being developed by Ngee Ann Polytechnic

Assimilable organic carbon (AOC) is a collective term for sugars, amino acids and other small organic carbon molecules that are present in water and can be readily used by microorganisms. Studies have found positive correlations between high AOC concentrations and the potential of bacteria re-growing in water distribution systems. This may cause biofilm to form in the pipe, resulting in operational problems like biofouling and biocorrosion. It can also subtly alter the taste and odour of water.

AOC compounds are small and cannot be removed by traditional sand-filtration methods during water treatment. Granular activated carbon (GAC) or biological activated carbon (BAC) filters are used instead. To effectively monitor the performance of these activated carbon filters, a good AOC measuring system is required to accurately detect and determine AOC concentrations in the water.

Conventional AOC analysis is carried out using bioassays and comprise two main stages. Stage I involves nine days of cell growth for two bacteria test strains. Stage II involves three to five days of quantification via plating (Fig. 1). The amount of bacterial colonies that have grown on the testing plates is then correlated with the AOC concentration of the water sample. This process, however, is laborious and time-consuming.

Zhou Xingding and his colleagues at Ngee Ann Polytechnic are developing a new method (Fig. 2) to address these challenges. The team is attempting to automate the quantification of bacteria in stage II, by modifying the two bacterial test strains so that they express different fluorescence protein genes. The concentrations of these fluorescent strains can then be measured simultaneously using a flow cytometer. This could reduce the assay time for stage II to just a few minutes.

In addition, the team plans to obtain fast-growing test strains to speed up the stage I process. Methods such as the use of classical mutagens, ultraviolet, heat shock, genome shuffling and transcription factor optimisation will be explored. Team member Tang Peng hopes to significantly reduce the time needed for stage I by obtaining fast-growing strains without compromising the carbon source utilisation spectrum. The team also aims to reduce the incubation time required by strictly controlling bacteria culture conditions, such as inoculum size and medium composition.

An additional advantage of the proposed method is the possibility of monitoring cell growth during the detection process, which can provide an early indication of the AOC concentration present in the sample while the detection process is still underway. If successful, this new method of detecting AOC will be as reliable and accurate as conventional methods while being 80 to 90 per cent more efficient. This would help water treatment operators in their work.

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Advancing the security of public infrastructure

Creating a modern industrial control system for cyber security research and training

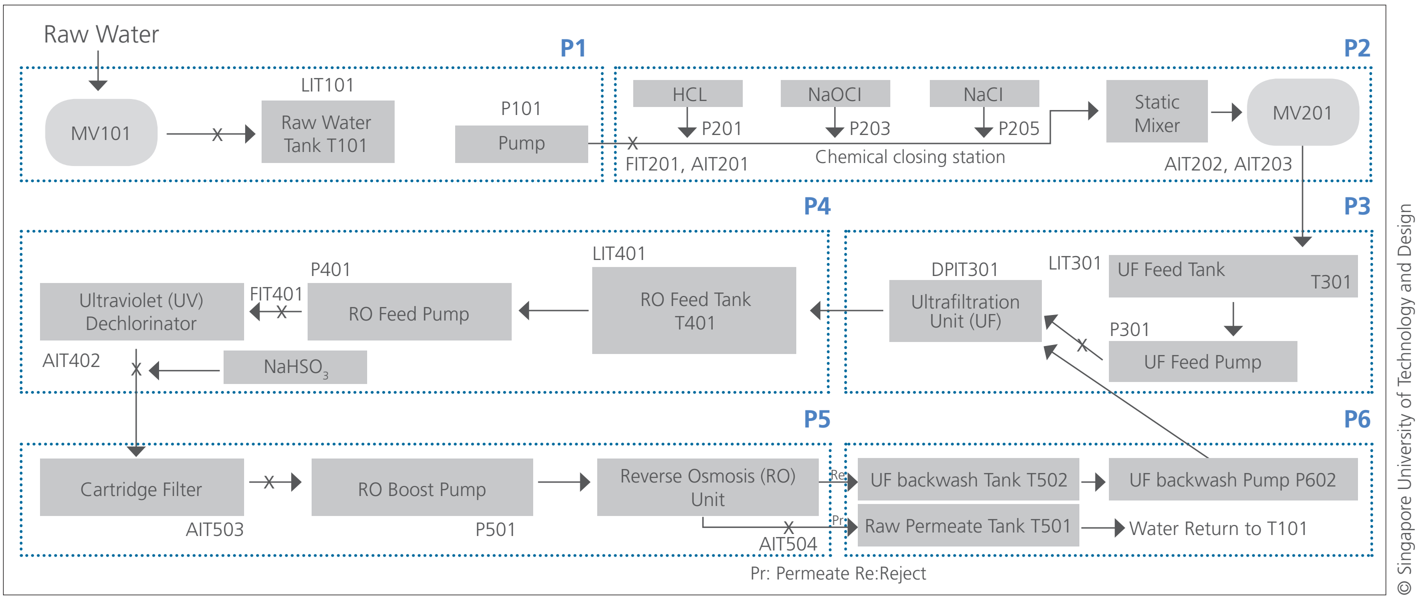

Fig.1: The physical water treatment process in the Secure Water Treatment (SWaT) test-bed. P1 through P6 indicate the six stages in the treatment process

Given the extent of connectivity that industrial control systems (ICS) operate in, security in the face of potential cyber attacks has been an emerging concern in recent years. However, due to lack of access to a live ICS, academic researchers have limited insight into ICS setups, and are prone to making misleading assumptions. To facilitate cyber security research, an ICS test-bed is therefore needed.

Aditya Mathur and his team from the Singapore University of Technology and Design (SUTD) have developed the Secure Water Treatment (SWaT) test-bed, a modern ICS for cyber security research and training. The SWaT test-bed aims to improve the understanding of the impact of cyber and physical attacks on a water treatment system, assess the effectiveness of attack detection algorithms and defence mechanisms under simulated attacks, and understand the potential cascading effects of failures in one ICS on another dependent ICS.

The test-bed mimics a large, modern membrane water treatment plant (Fig. 1). Using raw water from the campus water line, the test-bed has a six-stage process, with each stage controlled by a Programmable Logic Controller (PLC) (Fig. 2). A PLC is an industrial computer with supervisory control and data acquisition (SCADA) capabilities. It monitors on-line sensors such as water level sensors, and controls output devices such as valves based on a custom program.

P1 controls the inflow of raw water into P2, the chlorination station. The water then goes through an ultrafiltration (UF) unit in P3, a reverse osmosis (RO) feed pump and ultraviolet dechlorinator in P4 and a three-stage RO unit in P5. In P6, the effluent is recycled to backwash the UF unit. The PLCs have memory locations, known as tags, to record sensor data. These tag values are useful in implementing novel distributed attack detection algorithms. For instance, PLC 3 can verify tags in PLC 1 to check if a process invariant detected by sensors connected to those PLCs is true.

By manipulating the data that moves between the sensors, PLCs and the SCADA workstation, attacks on the SWaT test-bed can be simulated. Researchers simulate these attacks to investigate their effects on the test-bed and to assess the effectiveness of their attack detection mechanisms. Currently, the SWaT test-bed is fully functional (Fig. 2), and new sensors will be added to measure the chemical properties of water.

The SWaT test-bed is an active and realistic environment for real-time cyber security research. Looking ahead, it will be connected to a water distribution test-bed and an electric power test-bed to assess the impact of attacks' propagation and the cascading effects of simultaneous attacks on interconnected test-beds.

Fig. 2: The SWaT test-bed

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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 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.

Reducing membrane scaling for improved recovery in reverse osmosis

Changing flow patterns in reverse osmosis operations to increase recovery rates and reduce the use of chemicals

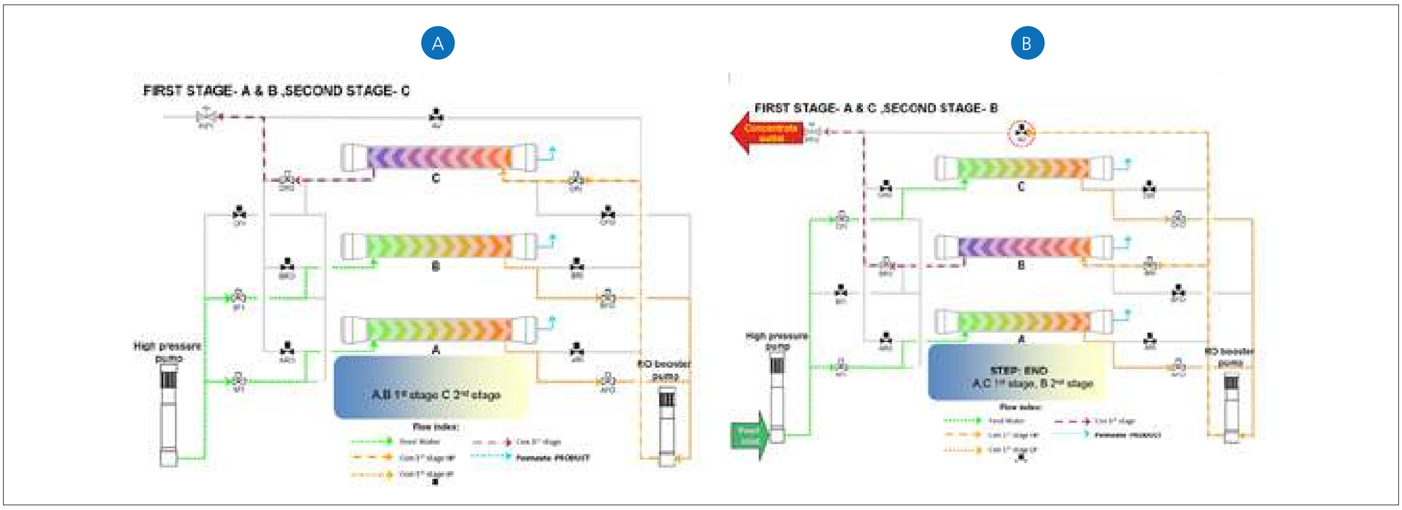

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Fig. 1: Flow reversal works by periodically switching the flow direction in a reverse osmosis (RO) system. Pressure vessels in the first stage (block B in illustration A) are switched with pressure vessels in the last stage (block C in illustration A) with simultaneous switching of the feed and concentrate connections. The updated flow pattern after the block switching is shown in illustration B

In NEWater production, reverse osmosis (RO) is a multi-stage process where treated used water is pushed through RO membranes to produce pure water, while the reject stream is channelled through successive RO treatment stages to increase water recovery. Over time, however, the performance of the RO system will degrade as sparingly soluble minerals build up in the retentate and form scales that clog the membranes' pores. The use of anti-scalants and chemical cleanings can only slow the degradation to a certain degree.

To address this problem, engineers from ROTEC have found a way to minimise scaling of the membrane. As supersaturated solutions of sparingly soluble minerals take a certain amount of time – known as induction time – to precipitate into crystal growth sites and form scales that clog membrane pores, reversing the flow of water in an RO unit could slow the build-up of scales.

As water flows through a multi-stage RO system, each successive treatment stage receives increasingly saturated feed water. This is why the tail membrane receives supersaturated water which is more prone to forming scales. By reversing the flow of water, the tail membrane becomes the lead membrane and receives less saturated water instead. Plant operators can periodically reverse the flow of water to ensure that the tail-end stage is always operated by a different RO treatment block, thus resetting the induction time that has elapsed back to zero and slowing the build-up of scales, all without physically changing the set-up of the RO system.

This flow reversal technique is currently being studied at PUB's Kranji NEWater Factory, where treated municipal used water is further purified via a two-stage RO process to produce high grade, ultra-clean reclaimed water. An existing RO treatment train, which has a production capacity of 444 cubic metres per hour and operates at 75 per cent recovery, has been retrofitted to become a three-stage process with flow reversal capability (Fig. 2). This was achieved by adding seven pressure vessels to the RO train, and then dividing all the pressure vessels into three stages instead of two. Automated valves were installed at both ends of the pressure vessels that will serve as the first and third stages in turn. To control the timing of the block switches, a programmable logic controller (PLC) was also added.

In this ongoing 15-month study, engineers from PUB and ROTEC are assessing the retrofitted unit's effectiveness and durability against scaling when it is operating at up to 90 per cent recovery. "By reducing the formation of scales in the water treatment process, flow reversal could yield significant improvements in membrane performance and improve recovery rates, reduce operating costs, and lessen the environmental impact associated with the frequent use of cleaning chemicals," said Dr Noam Perlmuter, ROTEC's chief executive and principal investigator.

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Fig. 2: Retrofitting project at Kranji NEWater Factory

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A multi-purpose treatment approach for integrated urban water systems

Achieving multiple benefits in an urban water system by replacing alum with sulphate-free iron salts

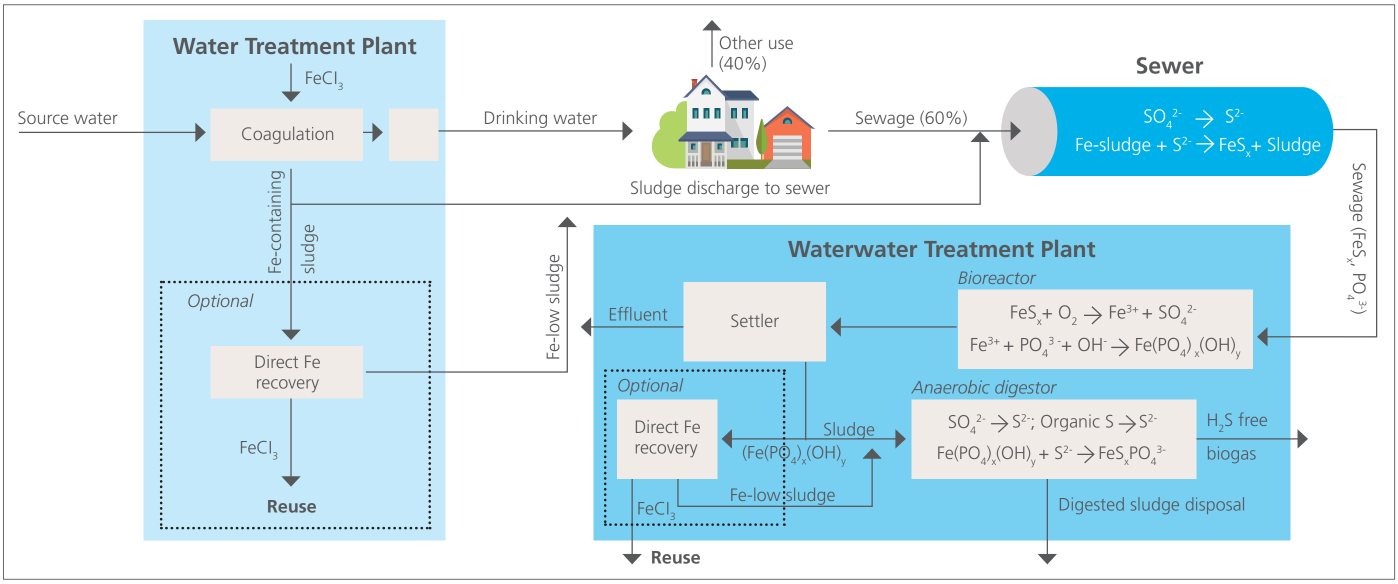

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Fig. 1: The proposed uses of iron salt in an integrated urban water system

The urban water cycle, which is the dominant flow path that water takes in engineered environments such as cities, is an interconnected system that involves a cycle of water collection, treatment, distribution and consumption. What happens in one step of the cycle has an effect on the other steps. An example is the regulated use of chemicals across the urban water cycle for treatment purposes, and the associated downstream "ripple" effects. A team from the University of Queensland's Advanced Water Management Centre (AWMC) is exploring how this interdependency can be leveraged in the case of coagulants used in water treatment.

Aluminium sulphate, also known as alum, is used as a coagulant in water treatment to neutralise negatively charged colloidal particles and agglomerate natural organic materials, so that these substances can be precipitated and removed. This process produces a large amount of sludge which needs to be disposed of properly.

The AWMC team has proposed replacing alum with sulphate-free iron salts such as ferric chloride. When the iron-containing sludge is discharged into the sewers, the ferric ions react with the sulphides present in used water and reduces the production of hydrogen sulphide accordingly, protecting the sewer network from its corrosive and odour-producing properties. As the sludge passes through the used water treatment process, this sulphide-reducing reaction continues, similarly resulting in the production of less hydrogen sulphide during the anaerobic digestion phase.

In addition, the iron in the sludge reacts with used water's dissolved phosphates, causing these to precipitate out. This is important in downstream treatment processes as used water with a lower phosphate concentration forms fewer scales on used water treatment systems, and produces better quality effluent for NEWater production.

The team from AWMC thus hopes to verify how sulphate-free iron salts can potentially play a beneficial role across multiple water subsystems. Fig. 1 illustrates how a single compound could function in an integrated urban water system.

To assess the applicability of this integrated approach in Singapore, a technical and economic feasibility study was conducted at PUB. The team is also carrying out pilot and field studies at AWMC (Fig. 2), as well as experiments involving laboratory-scale reactors to better understand what happens to iron in an urban water system. The findings from these studies will be used in the development of a model-based decision support tool, which water utilities can use to simulate the impact of iron salt applications throughout an integrated urban water system.

"The project will demonstrate how economic and environmental benefits can be achieved in urban water management by establishing close cooperation among utilities or departments providing different water services," said principal investigator Yuan Zhiguo.

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Fig. 2: The pilot sewer system used for the simulation project

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Optimising reverse osmosis systems to reduce NEWater operating costs

A new in-line device replicates systems' performance to give engineers operational insights and reduce operating costs

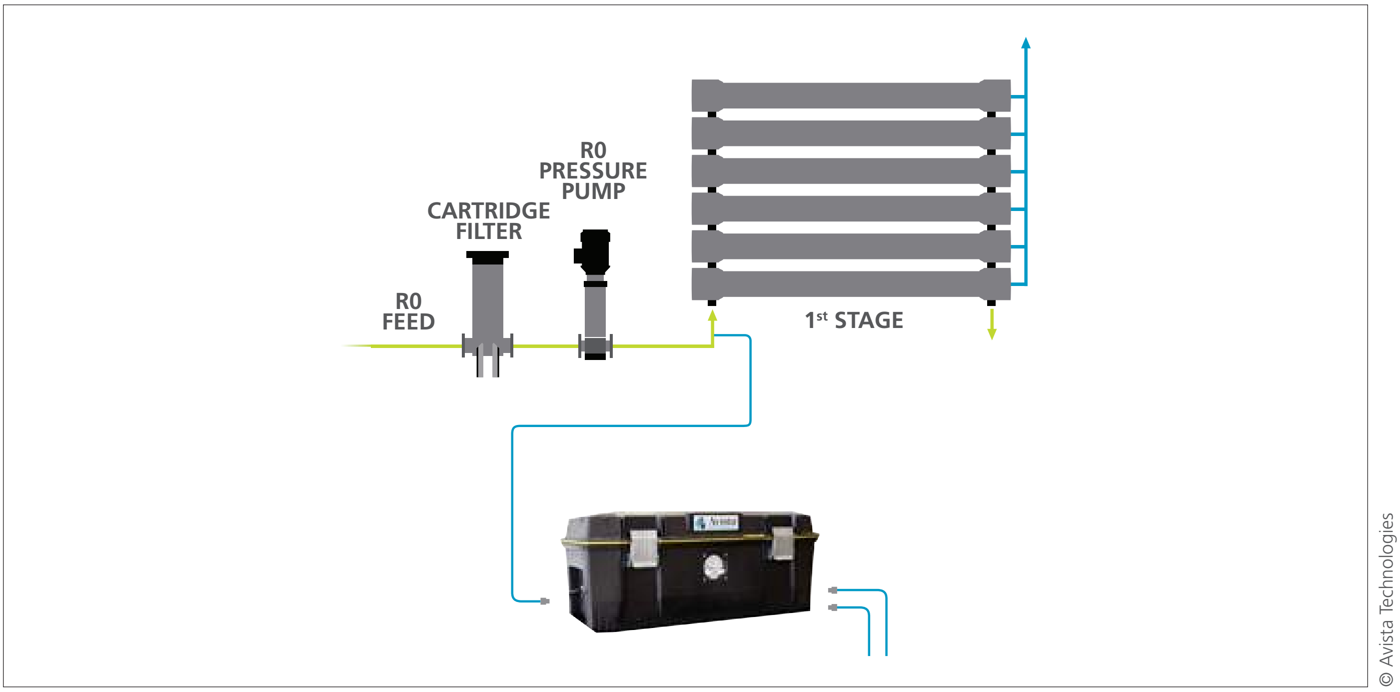

Fig. 1: The Black Box can be integrated into an reverse osmosis (RO) system at specific locations to simulate location-specific operating conditions

NEWater or high grade, ultra-clean reclaimed water, is one of Singapore's sources of water supply. The main treatment process in NEWater production is reverse osmosis (RO), where any remaining dissolved and suspended species, including bacteria, are removed from the feed water. However, the build-up of concentrated contaminants on the membrane over time renders the membrane prone to fouling and scaling. Timely cleaning of the membranes, as well as effective cleaners and proper cleaning procedures are essential to maximise their performance and service life.

To determine a membrane system's performance, plant operators monitor a set of operating parameters which include feed pressure, differential pressure, cleaning-in-place interval and membrane rejection. In addition, understanding the broad categories of contaminants that foul or scale the RO membrane surfaces would allow operators to assess the effectiveness of the existing cleaning and maintenance regime, and have it fine-tuned accordingly. However, this requires the system to be shut down for the off-line examination of the membranes, which would result in operational downtime and additional costs as the operating membranes would be sacrificed for the membrane autopsy.

PUB is working with Avista Technologies, to evaluate the health of RO membranes without removing them from the system using a technology called the Black Box, so that water treatment can continue uninterrupted.

The Avista Black Box is a standalone device that is mounted in a customised case, and can be installed at specific locations within a plant's RO treatment train. Each Black Box comprises small membrane samples that replicate the function of the full-fledged RO membrane in terms of operating flux and membrane material, allowing it to track the performance of the actual RO system (Fig. 1). As it is fully integrated into the treatment train, any contaminants that come into contact with the plant's RO membranes will also accumulate at the Black Box's RO membrane samples.

In this study, a Black Box was installed at Kranji NEWater Factory (KNF) for a period of three months until its performance declined and the volume of foulant material accumulated was sufficient for testing. The unit was then removed and disassembled for testing to identify the fouling mechanism of the RO membrane. Based on the results, a customised cleaning solution was formulated and recommended for KNF in order to better address and mitigate the specific membrane contamination issues encountered.

"The Black Box aims to determine the specific composition and deposition of foulants and/or scale material on the membranes, to help plant operators determine the best system optimisation solution," said Avista principal investigator Kent Goh. Optimising the RO system by using the Black Box can result in less operating downtime, reduced membrane cleaning and longer membrane life without taking the primary system offline.

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Centre for Remote Imaging, Sensing and Processing	Singapore
Centre for Water Research	Australia
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Deltares	Netherlands
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MWH Asia Pacific	Australia
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Nisko Telematics Systems	Israel
Nittetsu Mining Consultants Co.	Japan
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PWN Technologies	Netherlands
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Rehau Unlimited Polymer Solutions	Germany
ROTEC	Israel
Saline Water Conversion Corporation	Saudi Arabia
Beijing Scinor Water Technology	China
Sembcorp Industries	Singapore
Sound Global	Hong Kong
Star Water Technologies	Singapore
SUEZ	France
SystemNix Asia	Singapore
Tritech Engineering and Testing	Singapore
Trojan Technologies	Canada
United Engineers	Singapore
United Envirotech	Singapore
Utilis Israel	Israel
Veolia Environment	France
Visenti	Singapore
Vitens	Netherlands
Water And Sewerage Authority	Trinidad & Tobago
Water Optics Technology	Singapore
WH2O Technology	Singapore
Wisewater	Singapore
Xylem	USA
ZWEEC Analytics	Singapore

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