



INNOVATION IN WATER SINGAPORE



Water for All: Conserve, Value, Enjoy



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

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

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

R&D online portal *SINGwater*

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

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

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

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About the cover

A clear and bright day at Jurong Lake.

We Pave the Way for Water Innovation



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

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



Message from the Executive Director

Welcome to the sixth volume of *Innovation in Water | Singapore*.

In the last issue, we shared our progress on various research and development (R&D) initiatives to help Singapore achieve long-term water sustainability, including the development of biomimetic membranes for application in desalination.

This volume explores how Singapore invests in sustainable environmental technologies to strengthen the resilience of the water loop in the face of future challenges. This is along the same vein as the earlier issue, where we highlighted the ways in which Singapore is pursuing sustainable solutions to meet our water needs. In this issue, we look at various water innovations and research developments, in particular those that have lower energy consumption and production costs while enabling us to increase our water resources. One such initiative is the Integrated Validation Plant, which is being constructed to validate various energy-efficient used water treatment technologies in preparation for the future Tuas Water Reclamation Plant.

In the previous issue's "People in Water Research", we featured Dr. Andrew Benedek, our 2008 Lee Kuan Yew Water Prize Laureate, who shared his insights on the use of membranes to achieve water sustainability, and his thoughts on being the inaugural winner of the prestigious Lee Kuan Yew Water Prize. In this issue, Professor Shane Snyder shares his experience as a visiting professor at the National University of Singapore, as well as his views on his research on water reuse technologies and the implications for public and environmental health.

Beyond the stellar work produced by the researchers, the role of sound infrastructure is also imperative in achieving water sustainability in Singapore. The "Facilities Focus" section showcases PUB's water quality laboratories, a core component of our daily operations and a hub where innovative research projects on water quality are initiated.

Much of our achievements today would not have been possible without the support of our industrial and academic partners. To date, more than S\$314 million has been channelled into 435 R&D projects. A number of these projects are featured in the "Research Highlights" section. On this note, we hope to reach out to more water-related organisations and work together to reach greater heights in the field of water research.

We hope that you enjoy this sixth volume of *Innovation in Water | Singapore*, and gain deeper insights into our various initiatives. As we continue to improve our operations and existing infrastructure, we welcome potential collaborators with new R&D ideas to work with us to fulfil our mission in ensuring an adequate, efficient and sustainable supply of water for Singapore.

Chew Men Leong

Chief Executive, PUB, Singapore's national water agency

Executive Director, Environment & Water Industry Programme Office



Tapping on innovation to strengthen the resilience of Singapore's water supply

From having to depend primarily on external sources to expanding and diversifying its own water resources, Singapore has come a long way in a relatively short period of time. Singapore focuses on developing an adequate and sustainable water supply in the face of increasing water demand, through initiating and being involved in some of the most advanced and comprehensive technological research in the global water scene. Taking the lead role in the management of the country's water resources is PUB, Singapore's national water agency. Working together with other government agencies, academic institutions and partners in the water industry, PUB's research and development activities have catalysed the development of new ideas and technologies, and positioned Singapore as a global hub for water research and management.

Despite the challenges of a small geographical size and limited natural resources, Singapore has, over the years, successfully developed a diversified and robust water supply to meet the needs of the nation.

Today, water demand in Singapore is about 400 million gallons a day. With the projected doubling of the nation's water demand by 2060 and the challenges of urbanisation, climate change, and rising energy costs, there is a continual need for investment in water research and development (R&D) to ensure that there is an adequate and affordable supply of water in Singapore.

Meeting Singapore's water needs

Today, Singapore has Four National Taps, namely water from local catchments, imported water, NEWater and desalinated water.

With the opening of the Marina, Punggol and Serangoon reservoirs in recent years, two-thirds of Singapore is now water catchment. In the long term, this could be increased to up to 90% of Singapore's land area. This increase is achieved through the Variable Salinity Plant, a dual-function variable salinity plant that integrates desalination and NEWater treatment processes to treat water of varying salinity, allowing us to tap on the brackish streams and small rivers along the island's shoreline.

NEWater, a high-grade reclaimed water that is ultra-clean and safe to drink, was introduced in 2003. It has passed more than 100,000 scientific tests and exceeds the drinking water standards set by the United States Environmental Protection Agency (USEPA) and World Health Organization (WHO). NEWater is a major milestone for the nation, and has paved the way for greater advances in water R&D to ensure water sustainability in Singapore.

NEWater can currently meet up to 30% of Singapore's total water demand and is mainly being used for industrial and air-conditioning cooling purposes at wafer fabrication parks, industrial estates and commercial buildings. During dry months, NEWater is also used to top up the reservoirs.

By 2060, Singapore aims to increase NEWater capacity to meet up to 55% of the nation's demand. To fulfil this aim, plans are already underway with expansions of the existing Changi and Kranji NEWater factories, and the soon-to-be constructed NEWater factory in Tuas. These infrastructural developments will help increase Singapore's capacity for NEWater production.



In addition, the opening of the nation's first desalination plant in 2005 marked the beginning of Singapore's fourth National Tap. The Singspring desalination plant can produce 30 million gallons of water daily. A second and larger desalination plant, the Tuaspring desalination plant, commenced operations in September 2013, providing an additional 70 million gallons of water daily. Desalination capacity will be expanded progressively as well, so that it can meet up to 25% of our water demand by 2060.

Collaborations in water research

With its success in integrated water management, Singapore has advanced from managing water as a resource to leveraging on it as an economic asset.

Water and environment technologies have been identified as a key growth sector in Singapore, and the Environment & Water Industry Programme Office (EWI) was established to promote research and development in the field, grow the industry and position Singapore as a global R&D base for environment and water solutions.

With a funding of S\$470 million from the National Research Foundation (NRF), the EWI is well poised to meet its objective: growing Singapore into a global hydrohub for leading-edge technologies and furthering Singapore's vibrant research community.

The core areas of research focus are on Intelligent Watershed Management, Membrane Technology, Network Management, Used Water Treatment, Water Treatment, and Water Quality and Security.

These research topics cover a wide range of issues pertaining to water and are translatable to applied technologies, drawing interest from water organisations and government agencies both locally and globally. To date, there are over 130 water companies and 26 research institutions, creating a dynamic water research landscape in Singapore.

To further facilitate innovation, PUB's facilities, such as its waterworks, water reclamation plants and reservoirs also serve as a test-bed, and are available to both public and private sector organisations for the testing of new technologies.

The benefits that such on-site testing offers are great – technology developers have the chance to conduct trials under real operating conditions and fine-tune their research and products accordingly. Furthermore, these collaborations reduce costs and risks for technology

developers, and also often result in technological innovations which PUB can tap on, thus of benefit to Singapore. Over the past 3 years, close to 50 projects have been approved for test-bedding at PUB's facilities.

Cultivating an appreciation for water

While it is important to prioritise technological and infrastructural advances to ensure an adequate and sustainable water supply, it is just as crucial to educate residents and the industry about judicious water use.

This is done through a multi-pronged approach: pricing water correctly, mandating standards for efficiency in water usage, and facilitating programmes to encourage water conservation practices. These have successfully reduced Singapore's per capita daily domestic water consumption to 151 litres today. PUB's strategic aim is to reduce this consumption figure to 140 litres by 2030.

In addition, the Active, Beautiful, Clean Waters (ABC Waters) programme reminds city dwellers that water is vital not only to life itself, but also in ensuring the liveability of Singapore. Drains, canals and reservoirs are integrated with parks and green spaces, creating places for recreation and community bonding. This improves the aesthetics of the waterways and also brings people closer to water, creating opportunities for them to better appreciate and cherish this precious resource.

Wide reaching impact on water management

Singapore's innovations and forward-thinking investments in building a sustainable water supply has helped to position the nation as a global hydrohub and global leader in water management and technology. As Singapore continues to grow, PUB will continue to invest in sustainable environmental technologies to strengthen the resilience of Singapore's water supply. Some of the research being carried out looks at areas such as biomimetic membranes for low energy desalination and energy efficient anaerobic ammonium oxidation technologies for used water treatment.

The nation's efforts in R&D, education and conservation programmes will continue meticulously to ensure that the nation's water supply remains sufficient and ample. At the same time, Singapore's contributions to water research can also go beyond its shores and impact other countries positively.

Preparing for the Tuas Water Reclamation Plant

As the nation's economy and population grows, water demand in Singapore will continue to increase. Coupled with factors such as climate change and increasing energy cost, there is a need to ensure that Singapore's water resources remain sustainable and affordable in the face of future challenges. The treatment and subsequent reclamation of used water is a cornerstone in ensuring a sustainable supply of water for Singapore. Building on our current foundation in water recycling, the Tuas Water Reclamation Plant, the heart of the Deep Tunnel Sewerage System Phase 2, is being put in place to help meet the nation's growing need for water. In preparation for this new facility, which is expected to be commissioned in the early part of the next decade, PUB, Singapore's national water agency, is supporting research on possible technologies which will make the treatment of used water more energy-efficient, affordable and productive.



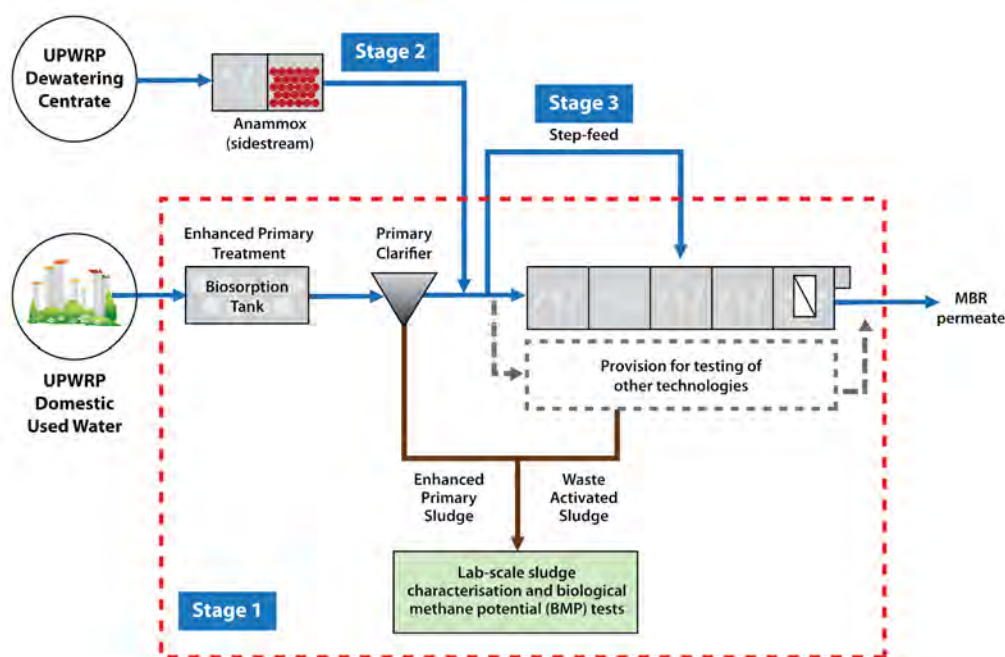


Fig . 1: Schematic of the Integrated Validation Plant (IVP)

For a country with a small geographical size and limited freshwater sources, ensuring a robust water supply has always been a priority. Over the last 50 years, Singapore has diversified its water supply, and ensured that our water supply remains sustainable and resilient.

A key component to the nation's achievements has been the successful planning and integration of water infrastructure with technology development ahead of demand. Therefore, with used water firmly established as a viable source of water for water reclamation, plans are in place to further advance operations and technologies in used water treatment so as to be able to treat water more efficiently and cost-effectively.

Used water management in Singapore

In line with Singapore's long term plans for integrated used water management, PUB will complete Phase 2 of the Deep Tunnel Sewerage System (DTSS) by extending it to cover the western part of Singapore. The Jurong Water Reclamation Plant (WRP) and Ulu Pandan WRP will progressively be phased out, and domestic and industrial used water from the western part of Singapore will be treated at the new Tuas WRP.

New technologies for Tuas WRP

Integrated Validation Plant (IVP)

The new Tuas WRP will incorporate technologies to improve its energy efficiency and manpower requirements. An Integrated Validation Plant (IVP) (Fig. 1) was thus commissioned at Ulu Pandan WRP in January 2014 to test various combinations of technologies that could potentially be implemented to treat the domestic used water coming into Tuas WRP.

The IVP was constructed based on a plug and play model, allowing for the testing of different treatment technologies at different parts of the process. Conducted in three sequential stages, a biosorption enhanced pretreatment (EPT) coupled with a low energy Membrane Bioreactor (MBR) (Fig. 2) is tested in the first stage. The plant performance data



Fig . 2: The Membrane Bioreactor (MBR) process being tested at the IVP

obtained from this configuration will then be used as a baseline for subsequent studies.

In the second stage, a side stream Anaerobic Ammonium Oxidation (Anammox) which can oxidise ammonia to nitrogen gas without consuming oxygen will be tested using dewatering centrate from the Ulu Pandan WRP solids handling facility. Sludge obtained from the plant will then be characterised for biochemical methane potential to determine the methane content for energy recovery. Once stable, the Anammox reactor will be integrated into the main IVP and studied further.

Finally, in the third stage, the bioreactor system will be further optimised by using a step feed. The aeration system will also be optimised using real time sensors linked to the dynamic blower control systems, allowing the blowers to respond to loading fluctuations more effectively, reducing



Fig. 3: Upflow Anaerobic Sludge Blanket-Ceramic Membrane Bioreactor (UASB-C-MBR) demonstration plant at Jurong Water Reclamation Plant



Fig. 4: A cassette of the ceramic membrane used in the UASB-C-MBR plant

overall aeration requirements. With effective aeration control, it would then be feasible to adjust the sludge retention time to achieve partial nitrification and consequently, test the main stream Anammox.

With the target of energy self-sufficiency in mind, operational experience with the solids stream treatment system together with the data collected from this study will allow PUB to understand the overall energy requirements for future demonstration and full scale plant implementation. In turn, performance targets for individual processes can then be identified to ensure efficiency. The tests being conducted will also serve as an opportunity for PUB to gain

operational experience and skills to operate the IVP treatment process (Fig. 3).

Treating and recycling industrial used water

Non-domestic water usage is also expected to increase significantly by 2060. In view of this, PUB, together with Meidensha Corporation, has commissioned a demonstration plant at Jurong WRP to evaluate the feasibility of an integrated Upflow Anaerobic Sludge Blanket-Ceramic Membrane Bioreactor (UASB-C-MBR) process to treat and recycle industrial used water.

The UASB technology uses certain kinds of bacteria which eat up organic contaminants and other unwanted components in the used water to produce bio-gas, which can be used to generate electricity. Ceramic membranes are used in the MBR process (Fig. 4) to handle the heavy duty used water containing chemicals and oils, which is typically very difficult to treat and recycle. This results in a more stable effluent quality, simpler maintenance, and a longer membrane life with less membrane deterioration. Together, the UASB-C-MBR treatment process is capable of reducing energy consumption, lowering sludge production and generating green energy by the conversion of organic components into methane gas.

The outcome of this demonstration plant at Jurong WRP will form a reference for the used water treatment facilities at the Tuas WRP. Accordingly, the product quality of the demonstration plant will be reviewed, and the system performance of this demonstration plant will be monitored under different feed and operating conditions for the purpose of optimisation.

The Tuas WRP reflects PUB's commitment towards research and innovation that is aimed at creating a sustainable and robust water supply in Singapore. With these new and tested technologies under PUB's belt, the Tuas WRP will be more eco-friendly, generating less sludge and producing more biogas for power.



PEOPLE IN WATER RESEARCH

Shane A. Snyder

Visiting Professor at the National University of Singapore

Dr. Shane Snyder is a Professor in the College of Engineering at the University of Arizona, and the Co-Director of the Arizona Laboratory for Emerging Contaminants. He also holds joint positions as a Professor in the College of Public Health and in the College of Agriculture. His research focuses on the identification, fate, and health relevance of emerging water pollutants. Together with his teams, he has published over 130 peer-reviewed manuscripts and book chapters on emerging contaminant analysis, treatment, and toxicology. Dr. Snyder has served two terms on the federal advisory committee to United States Environment Protection Agency's (USEPA) Endocrine Disruptor Screening Programme and was an invited expert panel member for the development of USEPA's Contaminant Candidate List 3. In addition, Dr. Snyder was a member of the National Academy of Science's National Research Council Committee on Water Reuse, and has served twice on the California Chemicals of Emerging Concern Expert Panels. He has recently been appointed to USEPA's Science Advisory Board for drinking water. Dr. Snyder is also a visiting professor at the National University of Singapore (NUS), where he collaborates with NUS faculty on research in water reuse technologies and the protection of public and environmental health.

The start of an adventure

What could possibly motivate a person to pack up a family of five, including identical twin infants, and travel for 30 hours to live and work on the other side of the world? For a scientist who is passionate about water research and technology, Singapore clearly has opportunities that supersede these travel challenges. Since 2011, I have participated in the Visiting Professor Programme (VPP) with the National University of Singapore's Environmental Research Institute (NERI). Our collaborative research with PUB has resulted in new advances in analytical and bioassay techniques to rapidly and comprehensively evaluate water quality.

Knowledge sharing

As the Research & Development Programme Manager for the Southern Nevada Water Authority in Las Vegas, I was impressed by Singapore's NEWater project. With only 110 millimetres of annual rainfall, Las Vegas has developed and implemented innovative approaches to water resource management. A key initiative is water reuse, accomplished through irrigation and return of highly-treated municipal wastewater (termed used water in Singapore) to Lake Mead, the reservoir that provides drinking water. Thus, I was anxious to visit Singapore to meet the experts and see their state-of-the-art facilities. In 2008, I attended the inaugural Singapore International Water Week (SIWW), and I have participated in every SIWW thereafter. After more than a decade of leading research and development (R&D) efforts in Las Vegas, I became a Professor of Environmental Engineering at the University of Arizona and co-directed a center focused on characterising emerging contaminants in water.

The chemical impact

Having earned degrees in chemistry and

toxicology, my career focuses primarily on determination of occurrence, toxicity, and treatment of chemicals often found in water supplies. While many chemicals are regulated to prevent potentially harmful exposures, the synthesis and release of new chemicals outpaces the ability of traditional toxicology studies to forewarn us of any potential consequences. Thus, we need to better characterise the chemicals entering water and determine their interaction within a complex mixture. Most chemicals in municipal used water are non-toxic at the levels present, although at times, trace levels of pharmaceuticals and steroid hormones have been linked to reproductive impacts on aquatic wildlife. Several chemicals in used water make excellent indicators for tracking water sources and entry points of contaminants to water resources to evaluate treatment process performance. Through the VPP, I have worked with NERI and PUB to develop efficient and reliable techniques to detect, characterise and remove emerging contaminants in water.

Innovation in analytical techniques

As emerging chemical contaminants are highly diverse, there are no standardised analytical methods for their analysis in water. Fortunately, with NERI and PUB's modern analytical laboratories and expert researchers, we have developed and implemented novel analytical techniques to detect and quantify a suite of diverse organic constituents in water. Common techniques often require sample volumes of one litre (or more), and involve labour and solvent intensive extraction and concentration for instrumental analyses. However, we have developed new on-line extraction methods that require only a few millilitres of water, and can achieve similar analytical sensitivity as conventional methods. Notably, the on-line extraction methods use only a

fraction of the organic solvents normally required, producing less environmentally-harmful waste. More recently, we have also been exploring methods that may not require extraction and allow direct analysis of water. While these analytical techniques allow rapid and sensitive identification of specific trace organic chemicals in water, they do not tell us the potential impacts of the complex mixtures of chemicals that can occur in the environment on living organisms. Hence, our VPP programme works on evaluating potential health effects from emerging contaminants as well.

Collaborating with NUS

NUS faculty possess renowned expertise in developmental toxicology and metabolomics, using a zebrafish model, which can be used in its native form or in a unique genetically-engineered version which fluoresces when exposed to certain contaminants. While my laboratory in Arizona has pioneered the use of various human and non-human cell lines for evaluating the toxicity of mixtures of chemicals, the genomic and metabolomic analyses developed at NUS enable more comprehensive screening of toxicity within an intact organism. The collaboration between NUS and the University of Arizona has resulted in new discoveries of developmental toxicity from certain mixtures of emerging contaminants, greatly shaping my own research programme in Arizona.

Overall, my experiences in development of analytical and bioanalytical characterisation techniques have contributed to the water research programmes at NERI and PUB, which will allow water agencies to gauge water quality better while providing additional evidence of water safety to customers.



PUB Water Quality Laboratory — Safeguarding the quality of water in Singapore



Fig. 1: A walk into PUB Water Quality Laboratory

As Singapore's national water agency, PUB's mission is to ensure an efficient, adequate, clean, safe and sustainable supply of water. It adopts an integrated approach in the collection, production, distribution and reclamation of water, managing the entire water loop in a holistic manner.

PUB monitors water quality from source (the time raw water collects in the reservoirs) to tap, ensuring the quality of water is well within the guidelines for its intended use. The quality of PUB's drinking water consistently meets the Environmental Public Health (EPH) regulations and World Health Organisation (WHO) Guidelines for Drinking Water Quality, and is safe for direct drinking from the tap. NEWater, which is produced from reclaiming treated used water, is ultra-clean water and is currently supplied mainly for industrial and commercial customers that require high-quality water. These standards are achieved through the extensive water analyses and R&D work which are conducted by PUB's Water Quality Office (WQO). The WQO also guides other PUB operational departments in the selection of appropriate treatment technology, management of water quality in the water loop and implementation of water safety plans.

PUB Water Quality Laboratory

Covering an area of 3,000 square metres, PUB Water Quality Laboratory forms part of WQO and is made up of six sections that each plays a specific role in ensuring a comprehensive analysis of all water samples (Fig. 1). These sections are General Chemistry, Inorganic Chemistry, Organic Chemistry, Microbiology and Biology, Advanced Biotechnology, and Quality Assurance/ Quality Control.

The laboratory is outfitted with a class 100 clean room, gas chromatography, high performance liquid chromatography and inductively coupled plasma testing equipment, and are able to carry out environmental and chemical analytical services (Fig. 2), including more than 600 inorganic, organic, radiological, microbiological and biotechnological parameters, through the use of regulatory and widely-accepted industry methods.

PUB Water Quality Laboratory supports daily operations by ensuring water samples are analysed promptly and accurately, and that results are communicated and interpreted correctly for operations and management. Water samples from various points in the water loop including the reservoirs, NEWater factories, water distribution network and waterworks are sent daily to PUB Water Quality Laboratory for analyses and interpretation by a team of 70 experienced professionals. About 400,000 tests on over 320 parameters are tested annually.

The laboratory also actively undertakes analytical investigations pertaining to customer complaint cases and incidents where the suspected presence of any external contaminants needs to be ascertained.

PUB Water Quality Laboratory forms the core backbone of PUB's goal to ensure quality water, and is consistently evaluated and validated through rigorous accreditation and certification assessments. The laboratory has achieved professional quality standards such as the SAC-SINGLAS ISO/IEC 17025:2005 and ISO 9001:2000.

Development of new analytical methods to improve capability of water quality analysis

With the implementation of stricter water quality standards and an increased focus on contaminants of emerging concerns, new methodologies are constantly being developed by PUB Water Quality Laboratory to ensure that it remains at the forefront of technology. This is essential in ensuring the integrity of the water supply.

One novel analytical methodology that has been developed by the organic chemists examines the various water matrixes and explores ways to achieve higher analytical efficiency. Incorporating online Solid-phase Extraction (SPE) combined with high performance liquid chromatography-tandem mass spectrometry, this new method offers an improvement over the offline SPE which is labour-intensive and time-consuming. In addition, the new method also

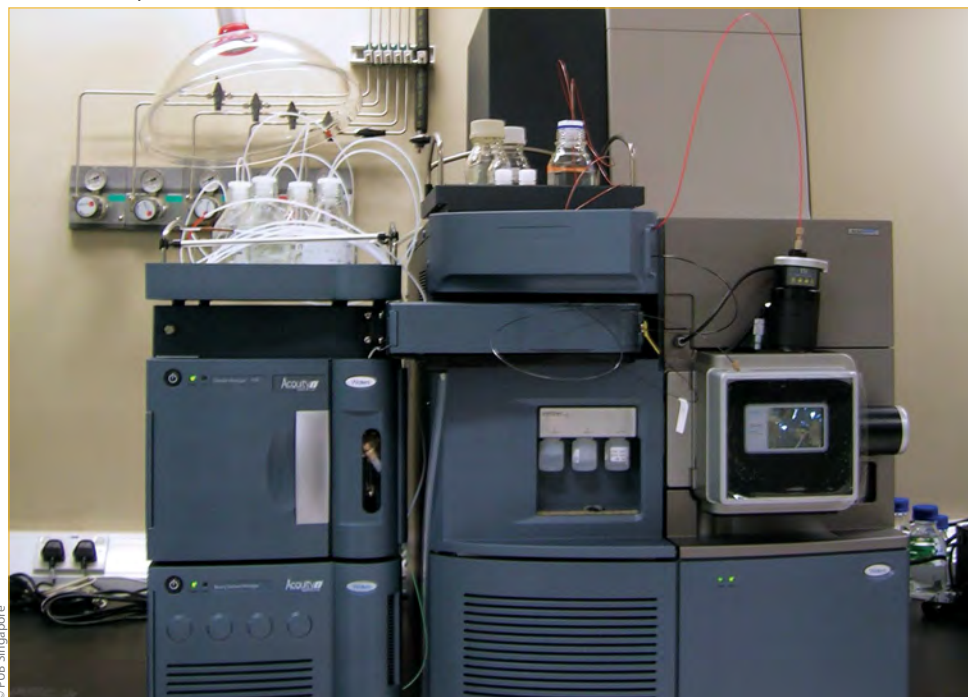


Fig. 2: Suite of equipments such as liquid and gas chromatography used to analyse water samples



Fig. 3: Professor Harvey Winters from Fairleigh Dickinson University works with PUB to develop improved strategies to control biofouling of membranes

uses lesser solvents and hence reduces the cost of analysis. This new method has been employed for analysis of 22 emerging organic contaminants such as endocrine disrupting compounds (EDCs) and Pharmaceutical and Personal Care Products (PPCPs). New testing protocols will also be developed using this new method to analyze other contaminants.

Another key research area focuses on DNA/RNA-based rapid detection of emerging microbial candidates such as amoeba, enteric viruses and bacterial pathogens in reservoirs. These organisms, if unmonitored in reservoirs, can pose challenges to diagnosis, treatment, and public health surveillance.

Conventional methods to identify an emerging microbe are difficult and time-consuming as the “new” microbe may have unknown traits. As such, identifying these organisms require a large array of techniques which could include cell cultures, cultivation using artificial media, extensive

microscopic examination, or serological techniques using surrogate antigens.

By establishing a protocol using polymerase chain reaction (PCR) which is based on the amplification of the unique genes of each microbial target, and through collaborative research such as a recent tie-up with the National University of Singapore on the detection methods of enteric virus, PUB Water Quality Laboratory will be able to rapidly detect some of the key emerging microbes of concern and prevent any potential health hazards from developing in a timely manner.

Collaborative research to improve operations

In addition, collaborations with water experts around the world allow PUB to leverage on experience and expertise from a global perspective. PUB collaborates with water quality experts on various research projects, and one example of this would be PUB’s work with the Fairleigh Dickinson University in America on the development of improved strategies to control biofouling of membranes (Fig. 3). This is especially important as reverse osmosis (RO) membrane-based processes play a significant role in water treatment in PUB.

The research examines how membrane biofilm can be dispersed. This will help predict the potential for membrane biofouling in any RO plant, and monitor the effectiveness of pre-treatment procedures in removing fouling organics from the RO feed.

Moving ahead, PUB will continue to encourage collaborative research and test-bedding projects, and look into measures that will improve processes and water quality analysis in the PUB Water Quality Laboratory. Such efforts will ensure that the laboratory continues to operate efficiently in view of increasing future challenges and remain at the forefront of water technology and innovation. For more information, please visit www.pubwaterresearch.com.sg.



Intelligent Watershed Management

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



In-situ three-dimensional water chemistry assessment

Using optical sensor on autonomous underwater vehicle to provide better understanding of spatial patterns of water chemistry in large water bodies

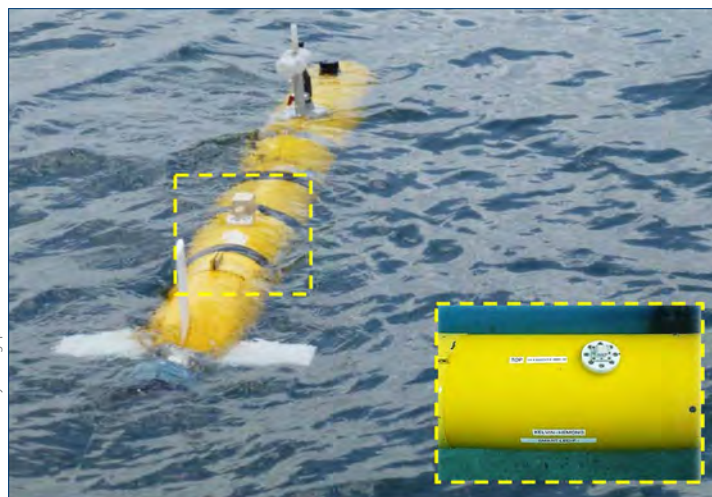


Fig. 1: The combined Light Emitting Diode induced fluorescence (LEDIF) – Small Team of Autonomous Robotic Fish (STARFISH) autonomous underwater vehicle (AUV) tested at Pandan Reservoir

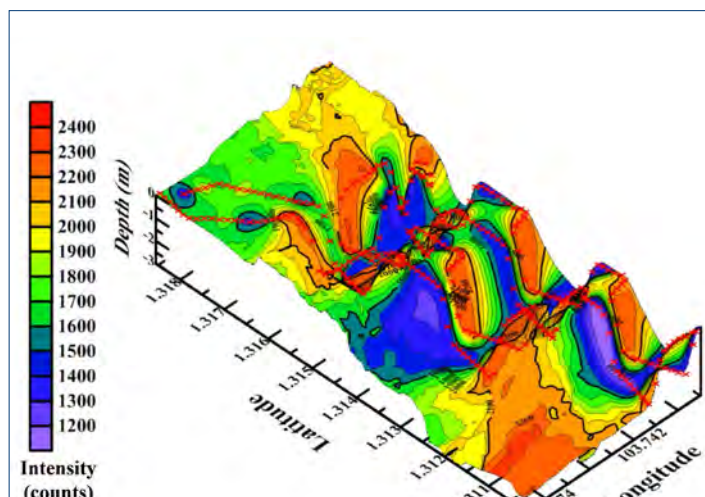


Fig. 2: A typical three-dimensional (3-D) chlorophyll mapping of LEDIF aboard the STARFISH AUV

Water chemistry assessment via sample collection has always been a labour-intensive exercise with many inherent physical limitations. The information collected is usually discrete in nature, with limited spatial extent that may not provide a detailed representation of the three-dimensional (3-D) water bodies.

The test-bedding project conducted by Singapore-MIT Alliance for Research and Technology (SMART) Centre and Tropical Marine Science Institute (TMSI) at Pandan Reservoir aims to mitigate such challenges through the construction of 3-D water chemistry maps. This study is possible through the use of Light Emitting Diode induced fluorescence (LEDIF), an optical sensor, and the Small Team of Autonomous Robotic Fish or STARFISH, an autonomous underwater vehicle (AUV) designed for cooperative sensing (Fig. 1).

LEDIF is developed for the in-situ real-time sensing of water chemistry, and is generalised for multi-platform deployment. Users are able to define and automate sensing tasks based on operation needs. Its tri-optical principles of sensing are suitable for measuring multi-species contaminants and natural substances such as chlorophyll pigments, chromophoric dissolved organic carbon, high molecular weight hydrocarbons, low volatile hydrocarbons, pesticides, and other organic

analytes in both freshwater and marine environments.

The STARFISH, meanwhile, is an extremely scalable robotic vehicle with a high level of hardware modularity and robotic flexibility that can be configured and deployed based on the needs of the research. Users are able to specify sampling tasks at points of interests to the vehicle. The vehicle then autonomously plans the paths to the points and executes the necessary tasks. The autonomy and flexibility is given by a group of software agents, acting in a similar manner as commanding officers on a navy vessel, that interact and decide on feasible solutions to accomplish the mission while providing adaptability to sensing needs.

For 3-D water chemistry assessments, LEDIF is mounted as payload onto the STARFISH and serves as the “scientist” to provide real-time water chemistry data. The STARFISH, together with the new “scientist”, is not only able to execute a pre-planned survey mission but can autonomously alter the mission in real-time to adapt to sensing needs. Both components have been designed to integrate at the fundamental level and function as one standalone instrument.

A series of trials were executed to demonstrate the capabilities of LEDIF-STARFISH to quantify algae biomass at selected areas of Pandan

Reservoir by programming LEDIF to measure the chlorophyll concentration. Traveling for more than 3 kilometres within 50 minutes, LEDIF-STARFISH has revealed potential areas of hotspots in the 3-D chlorophyll maps generated (Fig. 2), providing an unprecedented insight into the phytoplankton biomass distribution of the reservoir.

The results clearly demonstrate the strong capabilities of LEDIF-STARFISH to perform 3-D water chemistry assessment. These 3-D data can be used to study the effect of ambient conditions on spatial distribution of targeted analytes and complement real-time data from existing stationary monitoring platforms, allowing access to both spatial patterns and temporal trends of targeted water chemistry in the reservoir.

Researchers and affiliations

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Improving water quality through water plants

The use of water plants can reduce excessive nutrient levels at waterways in Singapore



Fig. 1: The native water grass (*Hygroryza aristata*) is one of the three plants tested for its nutrients removal ability



Fig. 2: The floating platform containing the water hyacinths, water lettuces and water grass was placed along Buangkok canal

Excessive algae growth can result when a water body becomes overly enriched in dissolved nutrients. This can severely affect the ecosystem of a water body and the quality of its water. The use of water plants to prevent such issues (known as eutrophication) and improve water quality in our local waterways is being considered as a viable and natural alternative to conventional pollutant and nutrient removal methods such as coagulation and flocculation. Besides being unobtrusive and environmental-friendly, the use of these water plants complement the image of Singapore as a City of Gardens and Water as well.

To evaluate the efficiency of water plants in keeping nutrient levels at appropriate concentrations, the Singapore University of Technology and Design, Nanyang Technological University and PUB worked together to assess three floating plant species — water grass, water hyacinth and water lettuce — for their ability to remove nitrogen and phosphorous during a 12-month test period.

Water grass and water hyacinth were selected based on their potential for phytoremediation, the ability to mitigate pollutants. The phytoremediation ability of these plants had previously been tested in a study exploring the application of various water plants to tropical water bodies. In addition, water grass (Fig. 1)

was also chosen as it is native to our waterways and suitable for waterlogged conditions.

For the study, 100 water hyacinths, 100 water lettuces and 10 bags of water grass were introduced at the start of each growth cycle and contained within stainless steel floating platform structures measuring 6 metres by 6 metres, supported by simple buoyancy fittings with a slip-proof connecting platform and netting attached below. These were placed along Buangkok canal in the north-eastern part of Singapore (Fig. 2).

Water samples were collected from selected cages located upstream, midstream and downstream of the waterway every fortnight, and sent to the laboratory for analysis on the amount of total nitrogen, ammonia, nitrate, ortho-phosphate, chlorophyll a, total phosphorous and other selected heavy metals that may be present. On top of this water sample analysis, monthly biomass removal exercises were also conducted, during which 7 plant samples of each plant species were randomly collected, dried and grounded into powder and analysed for phosphorus and nitrogen via gas chromatography and other standard chemical analytical techniques.

The results of the tests showed that while the water lettuce did not cope well under full-sunlight conditions, both the water hyacinth

and water grass had an average nitrogen removal rate of 125.7 milligrams (mg) and 23.6 mg per plant, and an average phosphorous removal rate of 7.5 mg and 1 mg per plant respectively, making both plants suitable candidates for implementation under Singapore's humid tropical conditions.

Also, the water quality over the 12-month sampling period never exceeded 1.5 mg per litre (mg/L) for total nitrogen levels and 0.12 mg/L for total phosphorous levels. These results demonstrated that with a careful selection of plants and a simple biomass removal management strategy, water plants can potentially provide a natural water treatment technology that is sustainable and easy to maintain in Singapore.

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Assessment of first flush in tropical catchments

Study aims to characterise the quality of stormwater runoff in tropical catchments for effective stormwater management



Fig. 1: Water quality of receiving water bodies, such as reservoirs, could be impacted by development activities



Fig. 2: Stormwater samples were collected to quantify the effects of first flush

There are growing concerns about the effect of development activities on runoff water quality and receiving water bodies (Fig. 1). This has raised interest in characterising catchment water quality and developing predictive water quality models for stormwater loads and concentrations.

In contrast to the large amount of research conducted on stormwater characterisation and modelling in temperate catchments, studies conducted on tropical catchments, however, have been limited so far. Considering that the rainfall intensity in tropical catchments is higher, resulting in larger runoff volume and a significantly different quality of stormwater, there is a need for research in this area.

Nanyang Technological University, together with PUB, embarked on a research project that studies the phenomenon known as “first flush”, under tropical conditions. First flush is defined as the disproportionately high delivery of either concentration or mass of a constituent in the initial portions of runoff. As a large amount of pollutants is usually present in this initial runoff volume, cost-effective approaches can be taken to treat this early volume of runoff while bypassing the remaining runoff. Therefore,

the first flush concept is important in effective management and treatment of stormwater pollutants. The research therefore aims to gain greater insight towards designing treatment measures based on first flush for stormwater management in the tropics.

To quantify the effects of first flush in tropical catchments, stormwater samples were collected from 10 sub-catchments with agricultural, urban and forest land uses in the Kranji Reservoir catchment for 20 months (Fig. 2). A total of 1,424 samples collected from 113 storm events were analysed for various parameters such as total nitrogen, total phosphorus, total dissolved phosphorus, ortho-phosphate and total suspended solids.

Results from the study illustrate that the first flush effect is not as pronounced as reported in studies conducted in temperate countries, possibly due to the frequent rainfall and large runoff volumes in Singapore’s tropical climate. In addition, the study also showed that agricultural catchments exhibit stronger first flush effects as compared to urban areas. This could be due to the erodibility of the soil layer as a result of surface disturbance. Quantitatively, the measurements demonstrate

that treating 30% of runoff may be beneficial towards removing total dissolved phosphorus and ortho-phosphate effectively. Also, the first flush strength of total suspended solids, total nitrogen and total phosphorus was found to decrease with area of catchment and increase with the imperviousness of the land.

The results of the study show that it could be more cost-effective to practise stormwater management or operate treatment facilities that are based on first flush treatment specific for tropical catchment areas, especially in agricultural catchments and at smaller upstream areas.

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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, and is now a key pillar of Singapore's water strategy.

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



Detecting membrane fouling at its onset

Early detection of fouling can help improve plant operations and prolong membrane lifespan



Fig. 1: Reverse osmosis is used to produce high-grade reclaimed water

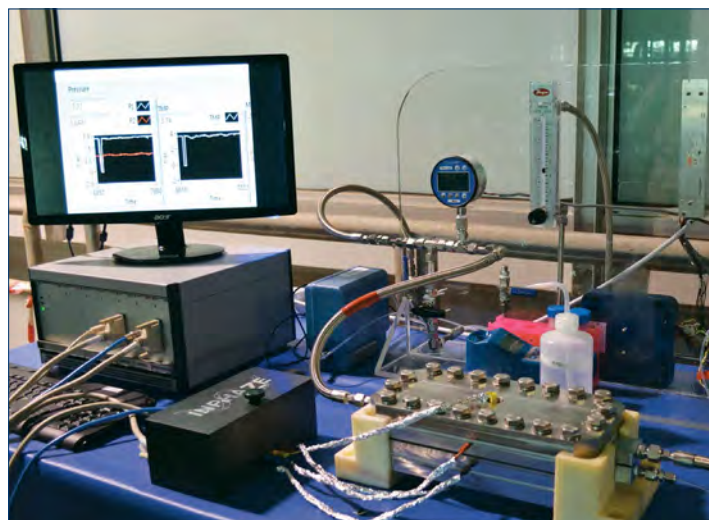


Fig. 2: Set up of the Electrical Impedance Spectroscopy Fouling Monitor tested at Bedok NEWater Factory

Reverse Osmosis (RO) is a key process in NEWater production (Fig. 1). The membranes used in the RO process are subjected to fouling when different materials present in the feed water are deposited on the membrane surface. This fouling can cause the water quality to deteriorate, increase energy consumption and treatment cost, and potentially shorten the membrane lifespan.

Currently, the increase in differential pressure (DP) between the feed and concentrate across RO membrane elements is used as an indicator of membrane fouling at PUB NEWater plants. One drawback of this measure is the fact that the monitoring process is passive and fouling may already have occurred even before any increase in DP can be observed.

To minimise fouling, it is more desirable for monitoring systems to detect fouling from the onset. Singapore Membrane Technology Centre (SMTC), in collaboration with INPHAZE Pty Ltd, an Australian-based scientific instruments company, has devised an Electrical Impedance Spectroscopy Fouling Monitor (EISFM) system. A non-invasive

fouling monitor, this system has been used by SMTC in extensive laboratory studies on colloidal, organic and protein fouling on RO membranes.

Laboratory studies by SMTC thus far have shown the EISFM to be capable of detecting initial fouling well before it translates into an increase in DP. In addition to giving predictive signs of fouling, EISFM is able to predict the extent of the fouling and to provide hints on which foulant types may be present in the system. Such predictions will allow operators to make informed decisions on the required preventive actions, which potentially reduces plant downtime and prolongs membrane lifespan.

To validate its laboratory findings, field trials are currently being conducted at Bedok NEWater Factory where a 'canary' RO cell, fitted with EISFM, is installed on a side stream of one of the RO trains (Fig. 2). The canary cell is designed to experience the same hydrodynamic conditions and to undergo the same cleaning pattern as the RO train. During the validation period, EISFM measurements will be taken periodically and

the responses compared against the actual DP changes of the RO train.

Should the trials be successful, the EISFM could be a unified and quantitative tool capable of online monitoring of membrane fouling through providing early warning signs. The information obtained can subsequently result in better advice towards more efficient cleaning cycles and chemical dosing.

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Improving the performance of gas-liquid membrane contactors

Use of porous organic-inorganic composite membranes can improve the performance of gas-liquid membrane contactors

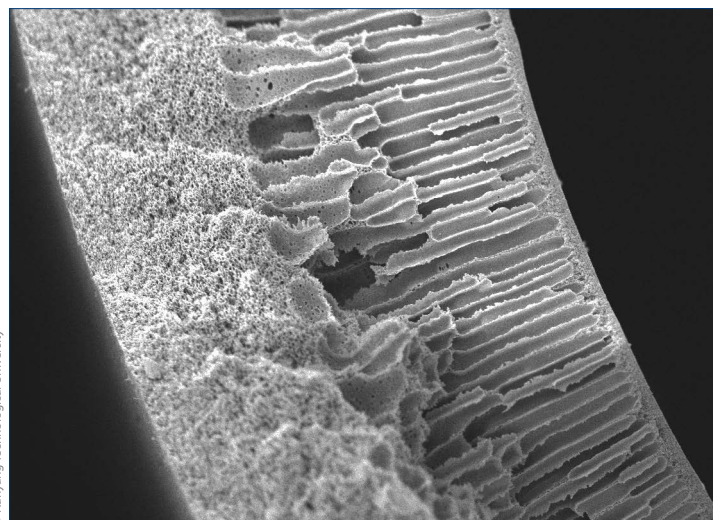


Fig. 1: Scanning electron microscope (SEM) image of the porous polyetherimide (PEI) hollow fiber membrane in its original state

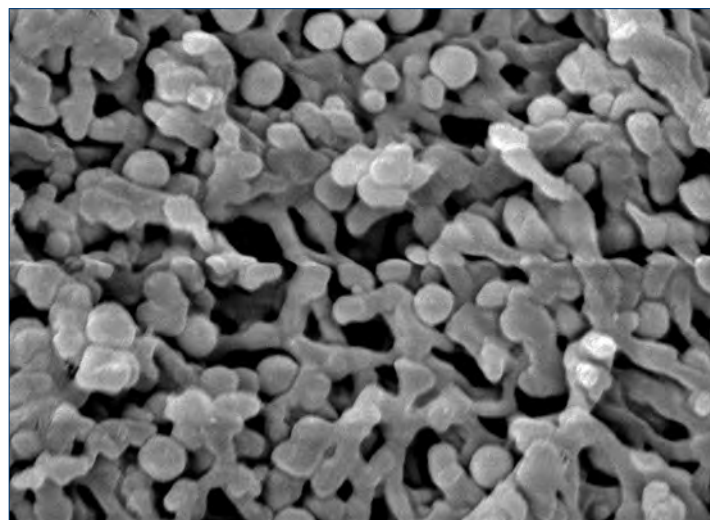


Fig. 2: SEM image of the PEI hollow fiber membrane with fluorinated silica (fSiO₂) nanoparticles

There is growing interest in the application of gas-liquid membrane contactors in the industries as these membrane contactors hold many advantages over conventional contacting equipment such as packed towers or bubble columns. With its higher surface area per unit volume, operation of independent gas and liquid streams, and compact modular structure, gas-liquid membrane contactors offer higher separation efficiency, greater ease of operation and flow adjustment, and allow for flexible applications in different scales of operation.

In a gas-liquid membrane contactor, the mixed gas stream and liquid absorbent flow on different sides of the membrane. The target gas in the mixture is transported through the microporous membrane and gets absorbed by the liquid absorbent to achieve separation.

For optimal performance of the gas-liquid membrane contactor, membranes with larger pore sizes are desired as larger membrane pore size translates to a lower membrane mass transfer resistance for gas transportation. However, the pore sizes of the membrane are usually limited by the issue of pore wetting, as a larger pore size leads to a lower liquid entry pressure into the membrane pore.

As such, Professor Wang Rong and her team from Nanyang Technological University

embarked on research to develop gas-liquid contacting membranes of larger pore size. The research utilised a membrane known as porous polyetherimide (PEI) hollow fiber membrane (Fig. 1), which has high surface porosity and large pore size. It was fabricated using a triple-orifice spinneret to minimise the membrane mass transfer resistance.

Using what is considered to be a novel approach, fluorinated silica (fSiO₂) nanoparticles were then incorporated into the membrane top layer to make the membrane surface highly hydrophobic and chemical resistant, preventing the membrane from wetting (Fig. 2). The resultant membrane is a new type of organic and inorganic composite membrane.

The performance of the membrane was then observed for a 60-day period with carbon dioxide as the feed gas and pure water or sodium taurinate aqueous solution used as the liquid absorbent to measure the carbon dioxide absorption flux. The performance was stable throughout the test period and outperforms conventional polymeric hydrophobic membranes in terms of superior gas absorption flux and outstanding long-term stability. This was due to the increase in surface porosity, pore size and pore interconnectivity of the membrane as well as the highly hydrophobic membrane surface.

The encouraging results of the experiment suggest that organic-inorganic composite membranes are viable solutions that can be applied to the membrane contactor processes for practical applications. The technology can potentially be applied in water reclamation plants to improve the quality of biogas recovered. The project team is currently furthering their research to improve the performance of the membranes, and to explore the use of these membranes for other applications, such as membrane distillation.

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Using ceramic membranes in water filtration processes

Study demonstrates the viability of ceramic membranes for water treatment



Fig. 1: The CeraMac® system developed by PWN Technologies uses a single stainless steel vessel to house up to 192 ceramic membrane modules



Fig. 2: The demonstration plant at Choa Chu Kang Waterworks has been installed since 2011

Ceramic membranes are corrosion resistant and can tolerate high pressures. While these membranes are commonly used in the industrial production of beer, wine and cheese, their large scale-application in water treatment has been limited as the high implementation costs makes it economically unfeasible.

PWN Technologies, a Dutch advanced water technology company, has developed an innovative technology, known as CeraMac® (Fig. 1). CeraMac® has the potential to greatly reduce the capital cost of ceramic membrane systems by using a single stainless steel vessel which can house up to 192 ceramic membrane modules. This significantly reduces the quantity of stainless steel and valves required and increases productivity, compared to conventional designs where each stainless steel casing only holds an individual membrane module. In addition, the design of the system allows for all the membrane modules in the vessel to be

backwashed concurrently, reducing the downtime during a backwash from minutes to seconds

An earlier pilot study which was conducted at Bedok NEWater Factory affirmed the potential of the system with promising results. Following the success of the pilot study, PWN Technologies set up a demonstration plant at Choa Chu Kang Waterworks (Fig. 2) to evaluate the performance of the CeraMac® system in terms of product water quality and operational efficiency over a period of 18 months.

The setup in the demonstration plant consisted primarily of a stainless steel vessel housing 19 ceramic membrane modules and a stainless steel backwash vessel. Testing was conducted using settled water dosed with ozone as feed water to the ceramic membranes. This is possible as the ceramic membranes are made up of aluminium oxides which are resistant to the oxidative power of ozone.

It was also further observed that adding ozone enhances the filtration process significantly by achieving a higher flux with lower transmembrane pressure, while maintaining a lower fouling rate and higher recovery. This is a clear advantage of ceramic membranes over the polymeric membranes, which are unable to tolerate ozone additions.

Overall, the encouraging results from this demonstration study have highlighted the application of ceramic membrane technology as a viable option for water treatment processes.

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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.



Predicting potential water pipe failures ahead of time

New technology aims to predict where pipe failures are most likely to occur in the water distribution network

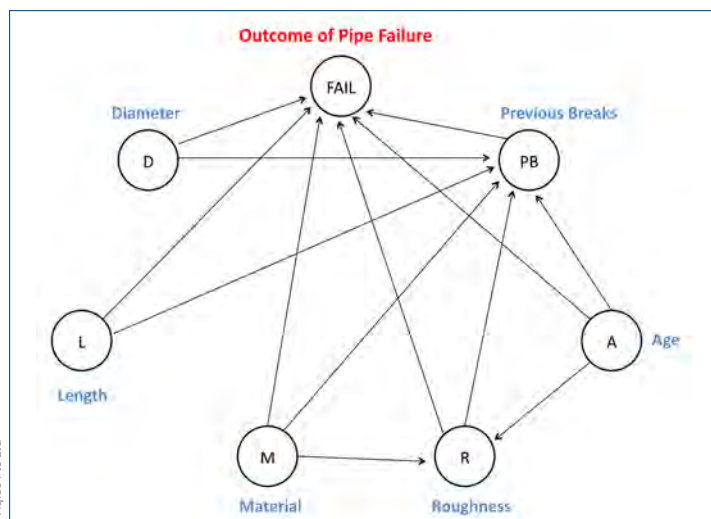


Fig. 1: The Bayesian Network (BN) model incorporates different parameters into its prediction of pipe failures

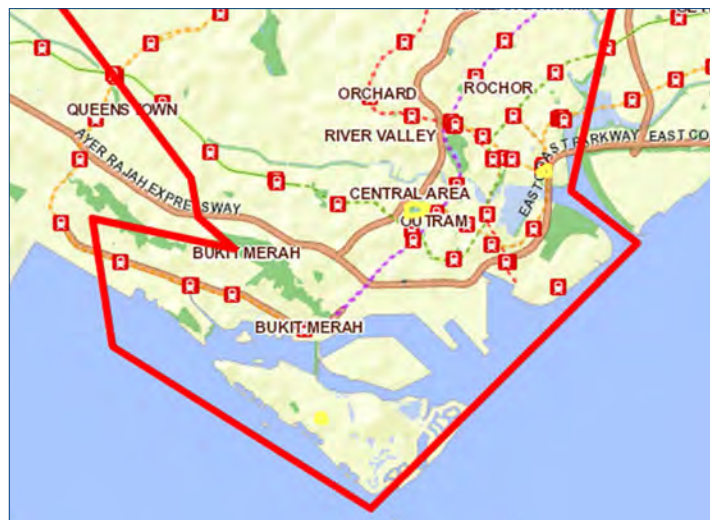


Fig. 2: The study was carried out on the water distribution network in the Queenstown and Pearl's Hill Fort Canning area (marked in red)

Maintaining water distribution networks can account for as much as 80% of the total expenditure involved in an entire water supply system. As water mains deteriorate structurally, the function of these pipes are also at a risk of being compromised. Among several other consequences, there is a risk of increased breakage rates and decreased network hydraulic capacity of these water pipes. As high financial resources are required to repair these networks, it is essential to implement the most cost-effective rehabilitation and renewal system for pipes.

One of the methods to predict pipe failure is by using the probabilistic model known as the Bayesian Network (BN) (Fig. 1), which uses graphical structures to represent knowledge about an uncertain domain. The objective of the model is to calculate the probability of a pipe burst, with the flexibility of the BN model allowing it to incorporate several parameters in the prediction process based on the characteristics of the pipe such as age, material, length, diameter or any prior leakage history.

Using a data-driven algorithm tool based on BN Modeling, PUB is working with Aqleo on a

study on pipeline failure prediction in water distribution networks. In the first phase of the project performed under an Economic Development Board grant from 2011 to 2012, a total of 375 kilometres of water mains in the water distribution network in the Queenstown area and Pearl's Hill Fort Canning area (Fig. 2) was studied. The objective of the study was to determine the pipes most vulnerable to failure in the water distribution network, and further score each pipe with a metric for failure probability.

Based on the available pipe characteristics and previous pipe failure history, the prediction algorithm was able to identify approximately 20-25% of the total number of pipes in the water distribution network for the studied area where failures are most likely to occur. The model also predicts and identifies areas that are more vulnerable to such failures.

In this second phase, the Geographic Information System (GIS) and user interface of the tool will be integrated into a unified framework that aims to allow PUB to employ the software as an operational tool in the long run. The project team is currently working on enhancing the prediction algorithm and plans

to include additional data types, such as soil condition, traffic load and system pressure. Due to the brief pipe failure history available, the team expects that the resolution of the results can be narrowed to less than 10% of the total number of pipes in the network where the occurrence of failure is most likely.

In the future, this improved tool will also be used to fill data and information gaps to improve the accuracy of this modelling. This will help further refine this failure prediction model of the pipelines to be under 2%, enabling PUB to focus on these higher risk areas for rehabilitation of our pipelines.

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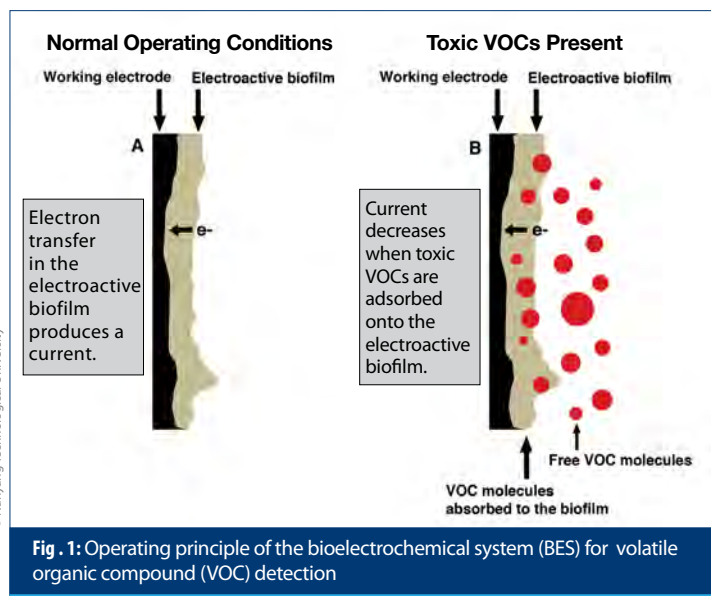
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Detecting volatile organic compound contamination in the used water network

Development of bioelectrochemical sensor can enable early detection of volatile organic compounds in the used water network



In areas where industries are located, volatile organic compounds (VOCs) such as benzene, toluene and xylene may inadvertently be discharged into the used water network. While the concentrations of these discharged compounds are very low, they could potentially be toxic to microorganisms. The presence of VOCs can also contribute to the failure of downstream used water treatment processes through the direct inhibition of biomass growth, and could potentially pose a hazard if the VOCs are not degraded during the biological treatment phase of the treatment process and are discharged in the effluent.

Early detection of VOCs can therefore protect the biomass in water reclamation plants from toxic shock, which in turn safeguards the water quality and production of NEWater. Current methods for the detection of VOCs however, are costly and generally not capable of continuous on-line monitoring. There is thus a need for low-cost sensors on-site that can give alerts when raw used water is contaminated, enabling rapid intervention to avoid large-scale contamination in the used water network and downstream treatment processes.

The bioelectrochemical system (BES) is an emerging technology that exploits electro-

chemically-active bacteria (EABs) to sense toxic chemicals. It is being evaluated as a potential solution to more effectively detect VOCs in used water due to its low cost, small size, robustness and ability to respond to very low concentrations of contaminants.

The working principle of the proposed BES relies on the fact that used water contains numerous species of EAB. These EABs produce a background electrochemical signal which can be measured using a novel gas/biofilm interface BES (Fig. 1). Since most VOCs are toxic to EAB, the electrochemical signal is expected to decrease upon the introduction of VOCs in the used water network. The rate of decrease of the signal depends on the chemical nature and the concentration of the VOC contaminant or mixture thereof. This working principle provides a suitable strategy for rapid VOC detection in the used water network.

PUB and Nanyang Technological University are jointly studying how the performance of the gas/biofilm interface BES can be further enhanced with the use of engineered EAB communities (Fig. 2). Such a setup is constructed by fusing a reporter gene encoding an enzyme or a fluorescent protein to a promoter element that can be induced by the presence of a target VOC.

When the bacterial systems are exposed to the target VOC, the transcription of the reporter gene is enhanced and the increased level of encoded proteins can then be detected by measuring the enzyme activity or fluorescence. A direct correlation between VOC concentration and the reporter gene expression can therefore be established.

The research is expected to produce an improved BES capable of rapid and effective detection of targeted VOCs at lower cost compared to current commercial devices. The future goal for these sensors is to deploy them for real-time monitoring and early warning of VOC contamination in the used water network.

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Reducing water consumption with recycled heat

Recycling waste heat reduces water demand in cooling systems and saves energy



Fig. 1: Cooling towers that reject heat are an important component in the cooling systems of buildings



Fig. 2: Natflow's prototype heat exchanger developed and piloted at Changi General Hospital (CGH)

Water-cooled chillers are one of the most efficient ways to keep large buildings nice and cool for its occupants. These systems keep buildings cool in hot and humid Singapore by using cooling towers that reject heat from the building where water is vapourised (Fig. 1). The water used in these cooling systems translates roughly to 27 million gallons of water per day. Reducing the water demands of cooling systems – and saving energy in the process – was thus the subject of a research project funded by PUB.

The objective of the project by Singapore-based company Natflow in collaboration with A*Star SIMTech and Nanyang Technological University was to divert and use some of the heat captured by air conditioning from the cooling tower. Rather than releasing all the heat back into the atmosphere, the concept was to recycle this heat and use it to meet the hot water demand of the building. Consequently, with the reduced heat load discharged there, the cooling tower consumes less water. A prototype heat exchanger with a unique tube-in-tube design was successfully developed and piloted at Changi General Hospital (CGH) (Fig. 2).

At the pilot system in CGH, the hot refrigerant generated by the building's cooling system is directed to the heat exchanger to recover the 'waste' heat from the refrigerant. In the heat exchanger, the heat warms up the water, which is then supplied to the building's showers, laundry, canteen or other areas where hot water is needed.

Through this system, the heat exchanger is able to produce enough hot water at 60°C to meet the hospital's needs. Moreover, since this system makes use of a resource which would otherwise be wasted, it is a more cost-effective way of producing hot water as compared to using electric or gas-fired boilers. This translates into significant energy cost savings. In addition, to ensure that the hot water produced by the heat exchanger is safe for consumer use, the system also has in place a safety circuit to detect leaks and prevent contamination.

Although heat exchangers are not entirely novel, Natflow has successfully improved the efficiency of the heat exchanger by increasing the heat transfer area, thus reducing its footprint by 4 times from 16 square metres

(m²) to less than 4 m². The compact size of the heat exchanger is an important feature as space is a luxury in Singapore.

Taking into account the entire system, the amount of water savings achieved by the cooling tower is limited by the hot water demand of the building. Hence, the team plans to embark on a more in-depth study to improve the efficiency of the heat exchanger and integrate it with a power turbo-generator, thus maximising the recovery of the waste heat from the cooling system and further reducing the water demand of the cooling tower.

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Used Water Treatment

Singapore's research and development 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 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 effluent standards.



Combining technologies to achieve greater efficiency in used water treatment

Development of Moving Bed Bioreactor-Ultrafiltration compact plant can optimise treatment of used water



Fig . 1: Pilot system at Mann+Hummel's R&D Centre in Tuas



Fig . 2: Moving Bed Bioreactor technology with ultrafiltration membrane system at Ulu Pandan Water Reclamation Plant

In treating used water, Membrane Bioreactor (MBR) technology is valued for its high quality effluent and space-saving design, a result of incorporating the use of membranes in the technology. However, there are challenges, such as high power consumption, difficulty in maintaining the system, high investment cost and rigorous pre-treatment requirements.

Another used water technology that is gaining attention is the Moving Bed Bioreactor (MBBR) technology. It has a simple process design and stable operating system, which makes it a viable system for decentralised applications, and lowers energy requirements as a result of greater oxygen transfer efficiency. However, the MBBR system has its flaws as well, such as lower quality effluent.

With market studies showing annual growth rates of more than 10% for the application of these two technologies, it is clear that both technologies are highly favoured in the used water treatment industry. However, to date, there are only a handful of applications in the market that utilises a combination of both the MBR and MBBR systems.

With this in mind, Mann+Hummel (M+H) explored the development of a system that is able to combine the strengths of both the MBBR and MBR in a single unified system, optimising the performance of both processes. Riding on the MBR concept of using a submerged membrane, M+H combined ultrafiltration (UF) membranes with the MBBR process. The resulting MBBR-UF process is an easy and reliable treatment system for decentralised plants of small to medium capacity. In addition, this system comes with relatively low investment costs as the components required for the system can easily be fitted in standard containers, making such a system easily deployable.

To gather first-hand information and results of concept feasibility and general system layout, a pilot system was installed at M+H's R&D Centre in Tuas (Fig. 1). The results from this pilot system proved the concept behind the MBBR-UF system. As part of the next stage of research, the MBBR-UF system is currently being test-bedded at PUB's Ulu Pandan Water Reclamation Plant (Fig. 2).

The MBBR-UF test-bed aims to gain insights on how the system will fare in treating used water, given actual conditions in a water reclamation plant. The data obtained through this on-site test-bedding project will also provide reliable process design and operation data for further research and fine-tuning of the technology. Some of the key areas that M+H is looking into include the cost-effectiveness of different types of biocarriers, nutrient removal performance of the system, as well as the optimal filling ratio of the bioreactor in order to minimise energy consumption and maximise degradation rates.

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Low energy innovation for water reclamation

Combination of the Membrane Bioreactor and reverse osmosis process to achieve a more energy-efficient used water treatment system



Fig. 1: PUB's Kranji Water Reclamation Plant houses several research projects, including the combined Membrane Bioreactor-Reverse Osmosis (MBR-RO) pilot plant



Fig. 2: Toray's pilot plant couples the double-decked Membrane Bioreactor (MBR) to a Reverse Osmosis (RO) process

As limits for effluent discharge are tightened, more municipal and industrial used water treatment plants are choosing to use Membrane Bioreactor (MBR) technology because of the higher quality effluent produced. In addition, through coupling technologies such as combining the reverse osmosis (RO) process with the MBR system, treated water of NEWater quality standards can be obtained.

However, there are some drawbacks. For example, the high energy consumption of the MBR system as compared to that of the conventional activated sludge process remains a major challenge to overcome. Fouling of the RO membrane is another key issue of this combination of membrane processes.

To address this issue and assess the long term operational stability of the system, an MBR pilot plant was test-bedded by the Toray Singapore Research Center from 2011 at Kranji Water Reclamation Plant (Fig. 1). Three variables were selected for evaluation during this study: the reduction of scouring air volume for MBR, flux

level for MBR operations, and the disinfection method to control RO fouling.

Due to the smaller installation area compared to a single-decked MBR module, a double-decked MBR module was used to reduce the scouring air volume required. An RO membrane was coupled to MBR system to further treat the effluent to NEWater quality standards (Fig. 2) too.

The results of the pilot test have been positive so far, with the MBR system achieving stable operations at high flux and low trans-membrane pressure with adequate and continuous dosing of chloramine, as well as periodic maintenance chemical cleanings.

The total energy consumption of the MBR process during the test was an estimated 0.33 kilowatt hour per cubic metre (kWh/m³), an improvement over the typical energy consumption of 0.40 kWh/m³ for conventional MBR operations. The water quality of MBR filtrate is also able to consistently meet the requirements for RO feed water quality. In addition, the RO membrane could operate

stably without the need for chemical cleaning for more than 5 months with continuous dosing of chloramine. This can be attributed in part to the high feed quality of the MBR filtrate. The RO permeate also satisfied the requirements of NEWater quality, and no degradation of the RO membrane was observed during the operations.

Future research aims to explore the possibility of operating the MBR system at even lower energy levels of less than 0.3 kWh/m³ during extended periods of operations without the need for chemical cleaning.

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New technology for fluoride removal from industrial used water

Non-chemical Feed Filtration System coupled with Functional Powder technology help to remove fluoride from industrial used water

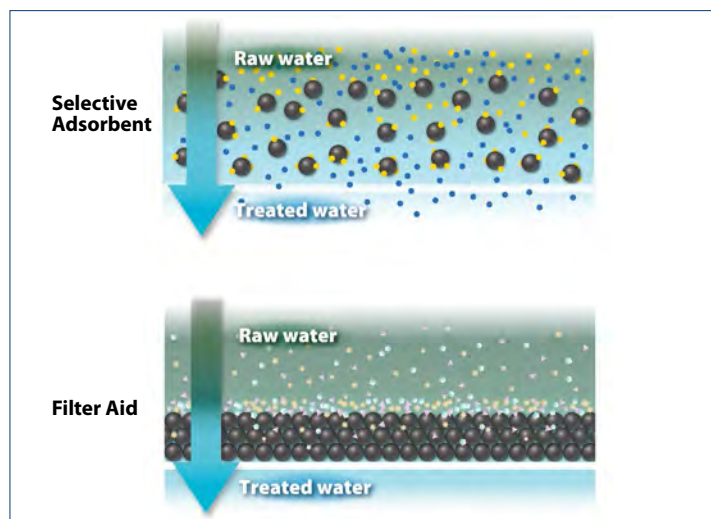


Fig. 1: Functional Powder can be used as an effective selective adsorbent and as a filter aid



Fig. 2: Non-chemical Feed Filtration System used to test the removal of fluoride

Fluoride is often present in high concentrations in industrial used water from semi-conductor factories. Due to its unique properties, the removal of fluoride by conventional water treatment methods is generally challenging.

Toshiba Asia Pacific's Aqua Research Centre has developed an advanced used water treatment technology, "Functional Powder" (FP), which can effectively remove toxins or recover valuable materials from industrial used water. The FP is able to adsorb high concentrations of chemicals and its structure is easily modifiable to target specific chemicals, including fluoride.

To remove fluoride, Toshiba coupled the FP with its coagulant-free "Non-chemical Feed Filtration System" (Fig. 1), allowing the FP to serve as an adsorbent for fluoride, as well as a filter aid. This low resistance filtration system is highly effective – it is able to significantly reduce the concentration of solids with diameters greater than or equal to 2 microns.

As the FP can be simultaneously recycled and reused, Toshiba has been able to operate the system at low operational costs. This system also does not require other chemicals such as coagulants, and as such, chemically-derived sludge is much lower when compared to using conventional adsorbents. This technology is therefore both sustainable and environmentally-friendly.

To validate this system, Toshiba test-bedded their pilot unit at PUB's filtration plant in Tampines (Fig. 2) to test its effectiveness in removing the high concentration of fluoride present in industrial used water from the semi-conductor factories. Test-runs showed that the system was able to reduce fluoride to a concentration of less than 15 milligrams per litre (mg/L) after treatment. The pilot unit was also operated continuously to evaluate the stability and robustness of the Non-Chemical Feed Filtration System. Results obtained showed that the system was able to achieve consistent fluoride levels of

15 mg/L or lower for more than 100 cycles in the treated product.

With this encouraging performance, Toshiba now plans to introduce this technology to developing Asian countries outside Japan, where the expansion of manufacturing industries is driving a need for industrial used water treatment technologies that are powerful, efficient and, at the same time, environmentally-friendly.

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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.



Keeping the waters in Singapore safe for recreational activities

The use of alternative microbial indicators can help to monitor Singapore's water bodies



Fig. 1: Recreational activities are carried out at reservoirs in Singapore



Fig. 2: Researchers carrying out water sample analysis for the occurrence of microbial indicators and pathogens

To encourage people to appreciate and cherish water, Singapore has been actively promoting the use of its water bodies for recreational water activities (Fig. 1). It is therefore important to ensure that microbial contamination does not occur, especially in a highly urbanised country such as Singapore.

Indicator bacteria such as the *Escherichia coli* (*E. coli*) and *Enterococcus* have traditionally been used as an indication of the presence of contaminants in water. However, several recent studies have shown that these bacteria are able to grow in the natural environment, which means that these indicator bacteria may also be present in water bodies when the water is not polluted. Moreover, there is increasing evidence that points to a lack of correlation between traditional microbial indicators and pathogens, with the presence of viable but non-culturable bacteria possibly complicating results further. In light of this, the viability of such traditional methods has to be reassessed.

To ensure the safety of water for recreational use and prevent the possibility of waterborne

diseases, PUB has been actively engaging in research to enhance our existing monitoring of microbial contaminants. One such study was conducted by the National University of Singapore and PUB to assess alternative microbial indicators, and whether they reflect higher correlations in accordance with the level of pathogenicity in surface waters from a tropical urban watershed.

Human and animal wastes were collected to evaluate the specificity of the alternative indicators. At the same time, water samples were collected from local catchment waters and analysed for the occurrence of indicators (both traditional microbial indicators and alternative indicators) and pathogens (Fig. 2). The specificity tests showed that traditional microbial indicators were present in both human and animal wastes. The results of the studies however, also showed that while it is difficult to differentiate human sources from animal sources using these indicators, alternative indicators such as human polyoma-virus and *Methanobrevibacter smithii*, showed high specificity to human wastes which poses higher risks of illness, and are thus a better option to trace human contamination sources.

Multiple linear regression models developed based on the two-year occurrence data set suggest that the application of alternative markers suitable for human-impacted tropical water environments can enhance the predictive models for pathogens. These markers can be incorporated into routine monitoring programmes which will allow PUB to source-track and ultimately improve water quality by effectively controlling contamination sources.

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Removing off-flavour compounds in water

Innovative electrochemical carbon nanotube filters adsorb and chemically oxidise off-flavour compounds on-site

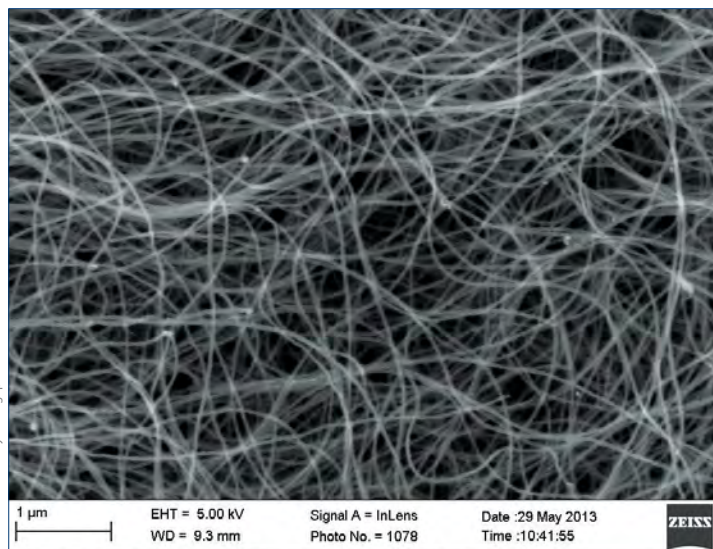


Fig. 1: Scanning electron microscope image of carbon nanotube (CNT) filters

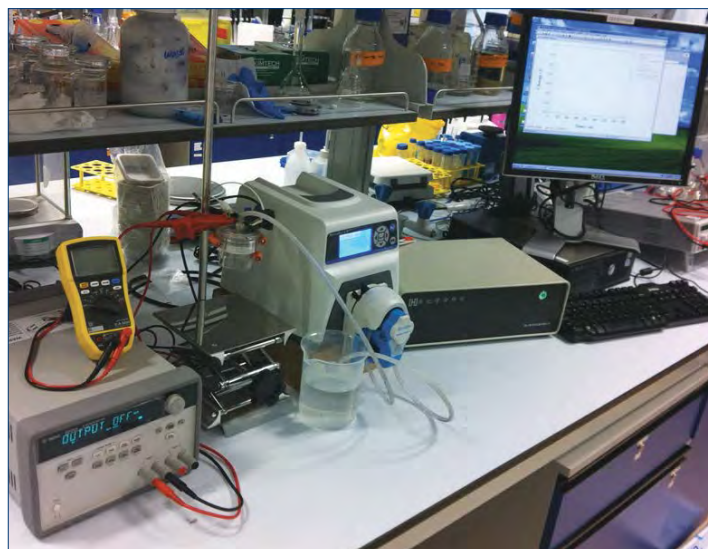


Fig. 2: Bench-scale electrochemical filtration system

Algal bloom is a global issue that has led to the production of off-flavour compounds, which can cause taste and odour issues in our drinking water. These off-flavour compounds have extremely low odour threshold concentrations (< 10 nanograms per litre) and are not easily eliminated through conventional water treatment processes such as coagulation, sedimentation, filtration and chlorination. Although conventional advanced oxidation processes (AOPs) such as ozone, ultraviolet, and/or hydrogen peroxide have been successfully applied to remove off-flavour compounds, these methods are usually costly when used in large scale operations.

A team led by Professor Zhi Zhou at the National University of Singapore and Professor Chad Vecitis at Harvard University are looking to resolve this issue with electrochemical carbon nanotube (CNT) filters. CNTs are easily formed into stable, porous, three-dimensional networks (Fig. 1) that can be used as electrochemical filters, and can potentially be used in contaminant removal and photo-electro-chemical processes for water treatment. A hybrid

electrochemical CNT filter can yield an oxidatively-active filter for increased pollutant-electrode contact and destruction. However, despite the various innovative aqueous electrochemical filtration applications, further research has to be conducted to produce a field-ready device with optimal results. "The main advantage of this electrochemical filtration system is that the target compounds can be physically adsorbed onto the membrane and chemically oxidised on-site at low voltage, so that membrane fouling can potentially be significantly minimised", says Professor Zhou.

Professor Zhou and his colleagues have constructed a bench-scale electrochemical filtration system (Fig. 2) to test the feasibility of removing two off-flavour compounds, geosmin and 2-methylisoborneol, and optimise operating conditions to improve removal efficiency. Their current results demonstrate that both compounds were removed by the CNT filters with 90% efficiency, at a short residence time of 1.2 seconds under an applied voltage of 1 volt and a

flow rate of 1.5 millilitres per minute. The next major challenge of this study is to scale up the filtration system, further increasing the flow rate without sacrificing removal efficiency of the filtration system. To provide the required electricity to drive the filtration setup, a solar panel can be utilised, so electrochemical filters may be widely used as a cost-effective, point-of-use treatment device.

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Understanding the potential effects of nanomaterials

Investigation looks at the cellular effects of exposure to nanomaterials in water

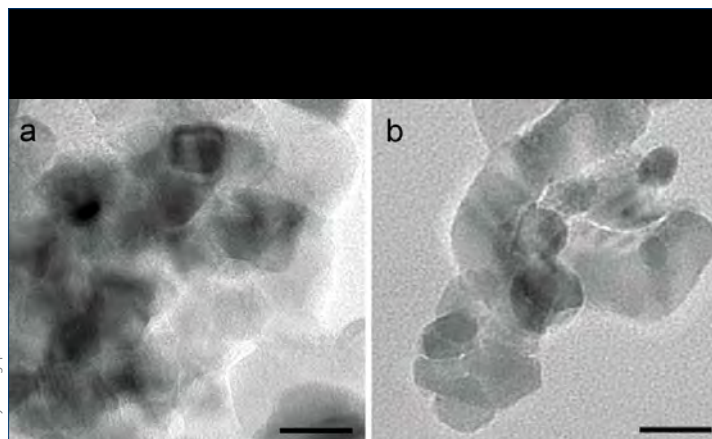


Fig. 1: Surface morphology of (a) Titanium Dioxide and (b) Zinc Oxide nanomaterials, viewed with a transmission electron microscopy (scale bar: 25 nanometres)

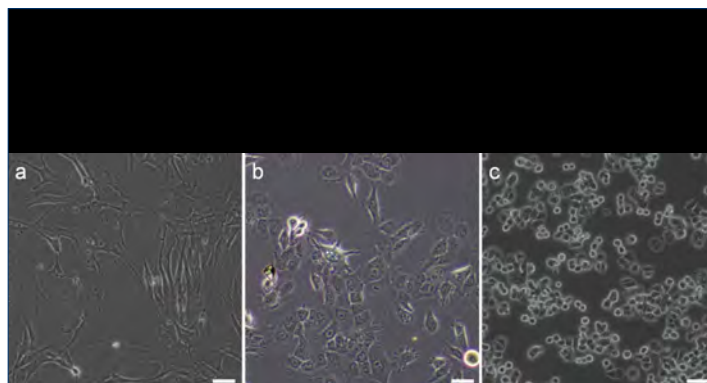


Fig. 2: The morphologies of human cells – (a) skin fibroblast, (b) mouth cells and (c) gut cells – used in this study (scale bar: 50 micrometres)

Nanomaterials are less than 100 nanometres in at least one dimension (Fig. 1), and are often exploited in consumer products; for example, anti-microbial clothing, paint, food colouring and additives and personal care products.

Nanomaterials have garnered significant interest from both industry and academia in recent years. According to the National Nanotechnology Initiatives in America, nanomaterials contributed \$251 billion to the global economy in 2009 and the number is estimated to increase further to \$2.4 trillion by 2015.

Given that our general population has likely been exposed to these nanomaterials, PUB has embarked on precautionary studies with the National University of Singapore (NUS), to address the cellular and potential health effects of these nanomaterials. The research was conducted using representative human cell lines, namely skin, mouth and gut cells to better evaluate potential effects (Fig. 2).

Aimed at understanding the biological effects of nanomaterials, the study investigates a wide range (12 orders of magnitude) of nanomaterial concentrations through a rigorous and comprehensive panel of effect indicators to determine any potential health effects.

With the aid of advanced assay methods including flow cytometry, the investigators were able to quantify cellular viability and vitality after treating the cells with three commonly found nanoparticles, namely titanium dioxide, zinc oxide and silver. Furthermore, a comprehensive surveillance of the effects on gene expression level arising from exposures to these three nanomaterials using quantitative real time polymerase chain reaction and immunoblotting methods will give deeper cellular and molecular insights.

When completed, the results gathered from this research will be able to provide valuable

quantitative information and insight about nanomaterials' impact on biological systems. With a more thorough understanding of any potential biological effects of nanomaterials, both NUS and PUB will be better informed to act in accordance to the research findings and implement necessary improvements to safeguard our waters.

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Water Treatment

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



Advanced oxidation process: The future of safe and clean drinking water?

Use of advanced oxidation process can enhance water treatment efficiency



Fig. 1: The container housing the advanced oxidation process (AOP) pilot plant utilised to conduct the study

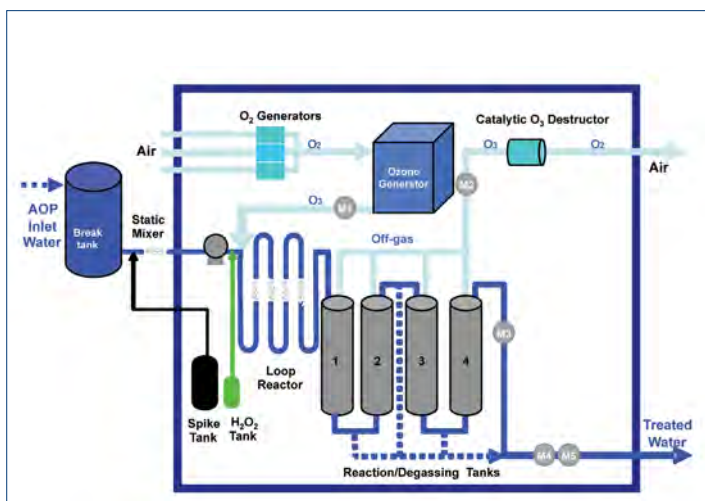


Fig. 2: Schematic of the AOP pilot system

Given rapid industrial and population growth, taste & odour (T&O) compounds and emerging organic contaminants that affect water quality are a growing concern for water utilities. PUB and Xylem Water Solutions recently concluded a two-year research project focused on the effectiveness of the advanced oxidation process (AOP) in removing these compounds in water under tropical conditions. The intention of the study is to ultimately develop an optimum AOP treatment process for a full-scale conventional water production plant based on the pilot results.

AOP is often considered an appropriate treatment to remove trace organic compounds and enhance treatment efficiency. This is due to the production of highly reactive hydroxyl radicals which have very high oxidation potential and react rapidly with most organic compounds – even with those resistant to other used water treatments – and rapidly break them down to harmless by-products.

The test campaigns during the period of the research was conducted using the AOP plant (Fig. 1) which was made in Germany

and supplied by Xylem WEDECO with PUB's organic laboratory assisting with the advanced chemical analysis. In total, the efficiency of AOP was assessed on the removal of 19 spiked organic compounds.

The test results were encouraging - the process was effective in degrading all *Endocrine Disrupting Compounds (EDCs)*, such as estrone and estradiol, which were spiked into the samples. For T&O compounds such as 2-methylisoborneol and geosmin, a 90% removal rate was achieved with AOP. Other than very few resistant compounds such as sucralose, most pharmaceutical and personal care products (PPCPs) were also removed by AOP treatment at a rate of 90-95% during the spiking study.

In addition to the analytical research, the AOP operating conditions such as the ozone dosage, hydrogen peroxide dosage, required reaction time, and energy consumption have been correspondingly optimised during the study. In terms of full-scale application, this could mean a more efficient and environmentally-friendly oxidation process (Fig. 2).

The results of this research proved that AOP could be utilised in the future as an essential barrier to ensure that utilities can supply safe and clean water to residents. It is increasingly seen as a viable solution to protect water utilities and institutions from growing threats such as deteriorating water source quality or water pollution. In addition, information obtained from the research will be helpful in guiding the design and upgrade of treatment plants, and improve the ability of water utilities to handle emergencies and critical situations.

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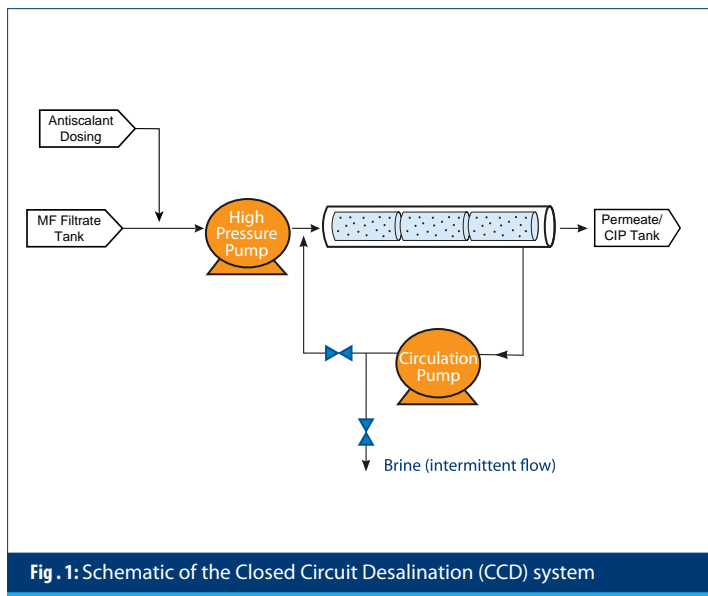
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Meeting the increased demand for NEWater

Closed Circuit Desalination can increase NEWater recovery



NEWater can currently meet up to 30% of Singapore's water demand. By 2060, Singapore's water demand is expected to double and NEWater capacity will be increased to meet up to 55% of this demand. One of the ways to achieve this is to increase the amount of NEWater that can be produced from existing NEWater factories.

This can be done by increasing the recovery rate so that more NEWater can be produced from the conventional Reverse Osmosis (RO) process. However, one challenge arising from this is the loss in production time. The RO membranes will need to be cleaned more frequently due to increased fouling and scaling tendencies. In addition, frequent cleaning of the membrane reduces its lifespan and leads to the need for more frequent membrane replacement.

Closed Circuit Desalination (CCD) technology, patented by Desalitech, Inc., is viewed as a viable alternative to reclaim water at high and flexible recovery rates. Developed to overcome the challenges of conventional RO systems, the technology is able to achieve higher and flexible water production

rates without compromising the quality of purified water, increasing the membrane cleaning frequency or increasing energy consumption.

The CCD set-up utilises standard RO equipment. A high pressure pump injects feedwater into a closed loop comprising a single-stage of standard RO membrane pressure vessels and a circulation pump. Purified permeate is produced at a rate that is equal to feedwater flow into the closed loop. The residual water from the process, which is termed brine, is re-circulated inside the closed loop until the desired percentage of purified water has been extracted. Brine is then flushed out of the closed loop, replaced by fresh feedwater, and the process then reverts back to closed loop operation (Fig. 1).

Demonstration trials using the CCD system are currently ongoing at Kranji NEWater Factory (Fig. 2) to establish the feasibility of producing NEWater at higher rates. The energy consumption and cleaning frequency of the CCD system are also being evaluated in these trials. In addition, the quality of NEWater

produced is being closely monitored to ensure that water quality is within required limits.

Initial results from this demonstration study have been encouraging, with the CCD system able to produce NEWater at a higher recovery rate and at the required quality. Despite producing NEWater at a higher rate, initial results have indicated that the energy required is the same and the membranes are being cleaned at a similar frequency as existing practices. The long term sustainability of the CCD system's performance is currently being assessed.

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Optimising granular activated carbon in water treatment

Novel research programme focuses on the optimisation and monitoring of granular activated carbon performance in water treatment

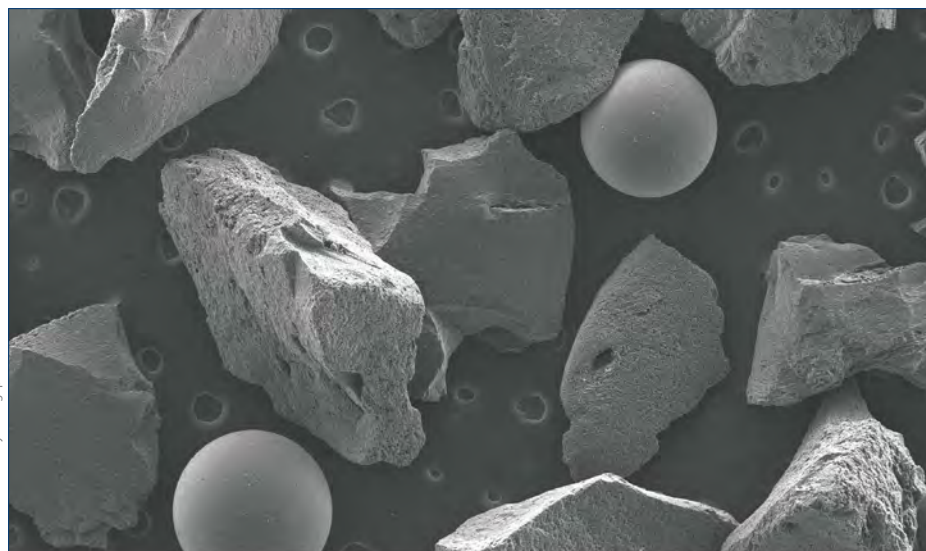


Fig. 1: Granular activated carbon (GAC) particles as seen using a scanning electron microscope



Fig. 2: A bench-scale GAC column used in the study

The surface water of our water bodies has been reported to contain trace levels of pharmaceuticals, personal care products, hormones, algal toxins, and other organic matter. This could be due to a myriad of reasons such as urban and agricultural runoff and aerial deposition in the original water source, and might lead to taste and odour issues, clogging of filtration processes, and depletion of oxygen in the water, thus resulting in a higher consumption of coagulation and oxidation chemicals during water treatment processes.

Granular activated carbon (GAC) (Fig. 1) has been identified as a relatively simple and efficient water treatment process that removes most trace organic chemicals. While advanced oxidation process technologies like ultraviolet (UV) and ozone can also remove certain chemicals in water, these technologies might result in the formation of unknown by-products. In contrast, GAC removes these chemicals by a process known as

adsorption, whereby the trace chemicals will adhere to the carbon surface without forming by-products.

To better assess the efficiency of GAC in the removal of trace organic chemicals and its relevancy in Singapore, PUB embarked on a joint research programme with Professor Shane Snyder from the University of Arizona and the National University of Singapore. The research aims to establish the optimal type of GAC and most efficient operational conditions using water from river and reservoir sources (Fig. 2). Data collected from the research will be used to develop correlations between organic contaminant attenuation and bulk water quality parameters.

The intention is to optimise efficiency and have a monitoring safeguard that allows quick determination of the GAC performance. This provides for a rapid and cost-effective characterisation of carbon systems for issues such as taste and odour compounds and other

organic contaminant attenuation. Professor Snyder aims for data from the research to be applied within the year.

The outcome of the research will provide PUB with a simple and highly effective means to gauge GAC operations, potentially reducing operational costs. In addition, PUB can gain a better understanding of the potential for trace organic chemical removal by GAC in different water environments.

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PUB Collaborators

Universities, Research Centres and International Organisations

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Agency for Science Technology and Research	Singapore	Sandia National Laboratories	USA
American Water Works Association	USA	Sembcorp R&D Collaboration	Singapore
Black and Veatch Global Design Centre for Water and		Singapore Centre on Environmental Life Sciences Engineering	Singapore
Centre of Excellence for Desalination	Singapore	Singapore Membrane Technology Centre	Singapore
Canadian Water Network	Canada	Singapore Polytechnic	Singapore
CDM's Neysadurai Technical Centre	Singapore	Singapore University of Technology and Design	Singapore
Centre for Environmental Sensing and Modeling	Singapore	Singapore-Delft Water Alliance	Singapore
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Centre for Water Research	Australia	for Water Eco-Efficiency	Singapore
Cooperative Research Centres	Australia	Stanford University	USA
Delft University of Technology	Netherlands	Stowa Foundation for Applied Water Research	Netherlands
Deltares	Netherlands	The Commonwealth Scientific and	
DHI-NTU Water and Environment Research Centre	Singapore	Industrial Research Organisation	Australia
DVGW-TZW Water Technology Center	Germany	Toray Water Technology Laboratory	Singapore
Evoqua Water Technologies' Global Water R&D Center	Singapore	Toshiba Aqua Research Centre	Singapore
Flinders University	Australia	Trent University	Canada
Global Water Research Coalition	Netherlands	Tropical Marine Science Institute	Singapore
IBM Centre for Intelligent Water Optimisation and Control	Singapore	Tsinghua Tongfang Asia-Pacific R&D Centre	Singapore
Imperial College London	UK	UK Water Industry Research	UK
International Desalination Association	USA	United States Environmental Protection Agency	USA
International Water Association	UK	University of Canterbury	New Zealand
International Water Resources Association	USA	University of Illinois at Urbana-Champaign	USA
KAUST Water Desalination and Reuse Center	Saudi Arabia	University of Maryland	USA
KWR Watercycle Research Institute	Netherlands	University of New South Wales	Australia
Massachusetts Institute of Technology	USA	University of North Carolina	USA
Michigan State University	USA	University of Oxford	UK
Nanyang Environment and Water Research Institute	Singapore	University of Queensland	Australia
Nanyang Technological University	Singapore	University of Waterloo	Canada
National Centre of Excellence in Desalination	Australia	University of Western Australia	Australia
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New Energy and Industrial Technology		Water Environment Research Foundation	USA
Development Organisation	Japan	Water Quality Research Australia	Australia
Ngee Ann Polytechnic Centre of Innovation for		Water Research Commission	South Africa
Environmental & Water Technology	Singapore	Water Research Foundation	USA
NUS-Environmental Research Institute	Singapore	Water Services Association of Australia	Australia
Peking University	China	WaterReuse Research Foundation	USA
Queensland Government	Australia	World Health Organisation	Switzerland

Water Utilities and Companies

Affordable Water	New Zealand	Koch Membrane System	USA
Aqleo	Singapore	Kuraray	Japan
Aquaporin A/S	Denmark	Kurita Water Industries	Japan
Arkal Filtration Systems	Israel	Liqtech	USA
Asahi Kasei Corporation	Japan	Mann+Hummel Ultra-Flo	Singapore
AWA Instruments	Singapore	Meidensha Corporation	Japan
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CH2M Hill	USA	Moya Dayen	Singapore
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Darco Water Technologies	Singapore	MWH Asia Pacific	Australia
DHI Water & Environment	Singapore	Natflow	Singapore
Dow Chemical Company	USA	Nitto Denko Corporation	Japan
Dragon Water Group	Germany	Optiqua Technologies	Singapore
DSO National Laboratories	Singapore	Orange County Water District	USA
Endress+Hauser Instruments International AG	Switzerland	PulverDryer	USA
Envipure	Singapore	PWN Technologies	Netherlands
Enviro Pro Green Innovation	Singapore	Rand Water	South Africa
Fluigen	Singapore	Rehau Unlimited Polymer Solutions	Germany
GE Water Technologies	USA	Saline Water Conversion Corporation	Saudi Arabia
Global Water Intelligence	UK	Sembcorp Industries	Singapore
Glowtec Environmental Group	Singapore	SIF Technologies	Singapore
GMF-Gouda Singapore	Netherlands	Starfish Enterprises	Philippines
GrahamTek Nuwater	Singapore	SUEZ Environnement	France
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Hyflux	Singapore	Veolia Environment	France
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Interactive Micro-organisms Laboratories	Singapore	Water Optics Technology	Singapore
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