INNOVATION IN WATER SINGAPORE

PUB

Water for All: Conserve, Value, Enjoy

An R&D Publication of PUB Singapore June 2011

Thank you for picking up the latest print edition of Innovation in Water Singapore. We hope you will enjoy reading all about some of the latest, most 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 abound 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.

To support this endeavour, PUB offers many opportunities for the collaborative development of new water technologies. If you are interested in finding out more about collaboration opportunities with PUB please log onto our website at http://www.pub.gov.sg/RESEARCH

PUB Singapore
40 Scotts Road #22-01 Environment Building
Singapore 228231
www.pub.gov.sg

Contents

NEWater Visitor Centre, Singapore

Message from the Executive Director

It is my pleasure to welcome you to the first issue of *Innovation in Water Singapore*. As a land-scarce island, Singapore has turned its water vulnerability into strength, leveraging on technologies and best management practices to meet the challenges of securing sufficient water resources to meet the strong and growing water demand from both the industrial and domestic sectors. This has led to the development of a vibrant water industry to support our water programmes and projects. To further sustain our efforts, the Environment & Water Industry Programme Office was set up in 2006 to coordinate a whole-of-government approach involving agencies like PUB Singapore (the national water agency), International Enterprise (IE) Singapore and the Singapore Economic Development Board to grow the industry and make Singapore a global 'hydrohub'. The key driver to this is technology development, which creates a vibrant ecosystem for research and development (R&D) on water and supports other water-related activities in the private and public sector. The initiative now consists of 23 research institutes and corporate laboratories, which, together with the local research community, have carried out over 300 R&D projects valued at S$185 million.

Singapore has also become a global test-bed for new ideas and technologies. International water companies recognise the ready access for testing their products in our water facilities and infrastructure, and the synergy in constructive collaboration with PUB Singapore and local research institutes. It is timely now to share the results of our R&D efforts through publication of the first issue of *Innovation in Water Singapore*. This publication will be released bi-annually.

Innovation in Water Singapore showcases a selection of R&D projects carried out in Singapore in six research areas: Intelligent Watershed Management, Water Treatment, Wastewater Treatment, Water Quality and Security, Network Management and Membrane Technology. Some of these R&D projects are conducted in-house and have a significant research component, while others are test-bedding projects where ready products are installed in our facilities for performance testing. The projects also range from laboratory-scale systems to demonstration plants.

Through this publication, we hope to reach out to those with ideas for water R&D to come forth and collaborate with us, and join us on this journey of discovery for a sustainable future for water.

Khoo Teng Chye
Chief Executive, PUB Singapore & Executive Director
Environment & Water Industry Programme Office

Marina Barrage, Singapore

Singapore water research and development for a sustainable water supply and the environment

Singapore carries out some of the most advanced and innovative water research across the whole water cycle. Leveraging on technologies and best management practices, Singapore is actively pursuing new technologies and processes to ensure security of supply to meet the ever-growing demands of its population and industry. This effort is spearheaded by PUB Singapore—the national water agency—and the Environment & Water Industry Programme Office established in May 2006 by the National Research Foundation. Research and development under these two agencies not only drives the innovative development of Singapore's water resources, but also benefits the people of Singapore by enabling them to make ever better use of that most precious of nature resources: water.

Water is a strategic resource for Singapore. A densely populated city-state of five million people, Singapore's demand for water comes to almost 1,730,000 cubic metres, or approximately 380 million imperial gallons, of water per day. In just 50 years, this demand is expected to double.

Rainwater is abundant in Singapore—some 2,400 millimetres of rain falls over the island every year—yet water is a scarce resource. The island's limited land area of some 700 square kilometres constrains the country's capability to store rainwater, a situation that is exacerbated by Singapore's lack of natural aquifers and groundwater. Reservoir catchments therefore play an important role in the water cycle of Singapore and with the recent completion of the Punggol and Serangoon reservoirs, the number of reservoirs for rainwater collection now stands at seventeen. These recent additions have increased the natural water catchment area from half to two-thirds of Singapore's land area.

Some 40 years ago, Singapore foresaw the need to harvest unconventional water sources in order to augment the supply provided by natural catchments. To this end, the government established a comprehensive research and development (R&D) programme and became an early adopter of new water treatment technologies. The success of this strategy is exemplified by the NEWater initiative, which now provides 30% of Singapore's current water needs. Five NEWater plants turn high-grade reclaimed water into ultraclean water that, after treatment and purification using advanced membrane technologies, exceeds the World Health Organization's drinking water standards. As 100% of Singapore is sewered, all wastewater can be collected and then treated using the advanced membrane processes.

Researching and Developing the Whole Water Cycle

Water research and development in Singapore is the responsibility of the country's national water agency, PUB Singapore, whose remit also extends to integrating the management of all aspects of the nation's water supply (**Fig. 1**). After rain falls, it flows into catchments before a network of drains and canals collects and channels the water to the reservoirs for storage. From there, it is treated to render it suitable for industrial and domestic use—including drinking. Wastewater collected by the network of sewers that serve the whole island is purified at the NEWater plants before being channelled to industry as an alternative water supply, or being reintroduced into the reservoirs as recharge water.

Singapore's water R&D programme is aimed at ensuring a safe, sustainable and continuous supply of water to all of Singapore and encompasses the whole water cycle to meet four specific goals: increasing Singapore's water resources, reducing production costs, enhancing water quality and security, and developing and growing the water industry.

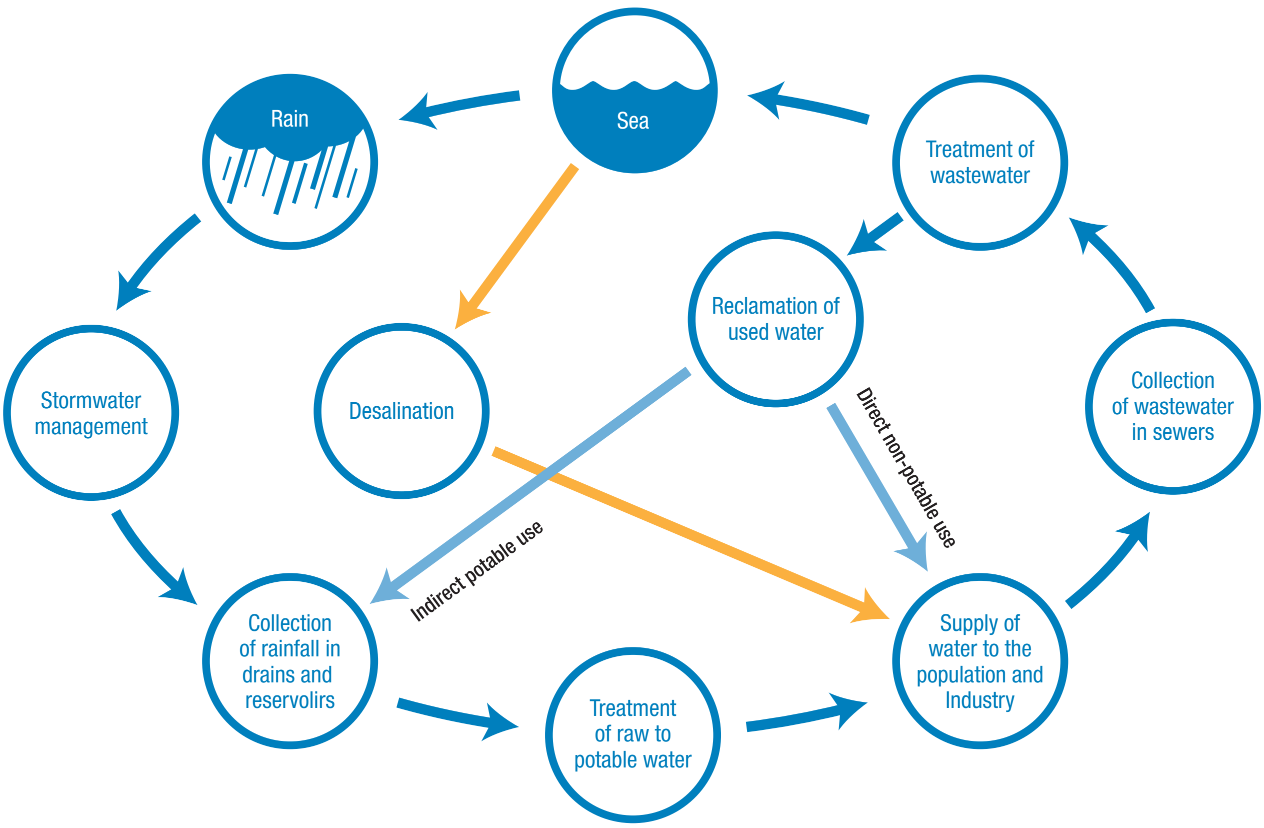


Fig. 1: Singapore's Water Cycle. With desalination and wastewater reclamation, water resources are managed within a closed water loop.

Singapore's Water R&D Goals

Increasing Singapore's water resources

Developing unconventional sources of water to augment Singapore's natural supply began in the 1970s. Advancements in water technologies saw PUB Singapore successfully introduce the NEWater technology to its supply network in 2003, and the fifth NEWater plant opened in 2010. PUB Singapore also successfully introduced desalinated water in 2005.

The effort to increase Singapore's water resources, which continues tirelessly, has overcome challenges in developing catchments. The Marina Barrage—built across the mouth of the Marina Channel in Singapore's central business district—and the Punggol–Serangoon Reservoir scheme in the northeast, for example, bring the total reservoir catchment area of Singapore from about half to two-thirds of the island.

Owing to ongoing improvements in treatment technology, PUB Singapore can now treat the water collected from these highly urbanised catchments to meet stringent drinking water standards on an economical basis.

Reducing production costs

Improving the efficiency of operations and maintenance work at water processing and treatment facilities translates into savings in production costs. By making improvements in the use of resources such as labour, chemicals, electricity and water, Singapore is keeping costs competitive in the face of challenges posed by ongoing urban development.

Ensuring greater environmental sustainability also requires improvement in current and new technologies. With local and international partners, Singapore's water R&D effort actively targets initiatives to lower energy use and cost in areas such as osmotic membrane bioreactors, membrane distillation and integrated anaerobic–aerobic used-water treatment processes.

Enhancing water quality and security

With the imminent introduction of more stringent water quality standards in Singapore, water utilities can no longer merely improve water treatment processes. They must also improve existing water quality monitoring and analytical techniques. Coupled with the growing awareness of emerging contaminants and the possibility of events external to a system causing contamination, increasing the speed and sensitivity of contaminant detection is also imperative so that utility operators can ensure the water they supply is safe to drink. Singapore's water research effort through the work of PUB Singapore and the Environment & Water Industry (EWI) Programme Office is actively collaborating locally and internationally to develop more sensitive and reliable analytical methods and instrumentation to improve water quality and provide water security.

NEWater – A product of Singapore's R&D efforts

Developing and growing the water industry through the EWI programme

To spearhead the development of Singapore's environmental and water technologies industries, the EWI Programme Office was established in May 2006 under the administration of the Ministry of the Environment and Water Resources. These programmes are now administered by PUB Singapore. In recognition of the strong economic growth potential of this industry, Singapore's government provided funding of S$330 million over five years to promote strategic R&D in this area. The work is designed to not only give Singapore's water industry a competitive edge in the global market, but also position it as an R&D base for environment and water solutions.

While the EWI office provides the overall direction and coordination of efforts in developing and growing the water and environment industry, PUB Singapore supports the EWI initiative by making available its R&D facilities in water technology for testing and collaboration. PUB Singapore also provides advice and collaborates with the industries in the environmental and water technology sectors to ensure that funded R&D works will have end-user applications.

Singapore's Water R&D Strategy

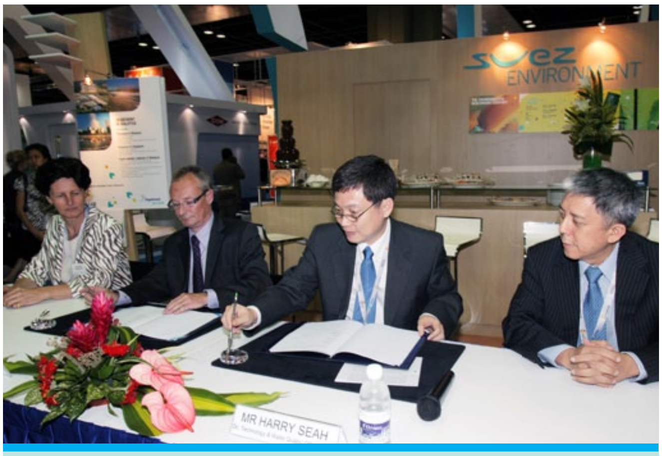
Singapore's approach to researching and developing the whole water cycle is divided into an upstream arm covering fundamental research and a downstream arm covering the testing of new technologies for downstream applications.

For fundamental research on projects with potential application at Singapore's water facilities, PUB Singapore leverages on the resources and expertise of Singapore's tertiary and research institutions. Concurrently, the Centre for Advanced Water Technology, PUB Singapore's in-house research arm, conducts research in water analytics, advanced water reuse technologies and water resources management.

Beyond fundamental research, PUB Singapore works closely not only with tertiary and research institutions, but also with the private sector. Private companies can test their new technologies at existing PUB facilities. This allows on-site testing under actual conditions, which is a key step towards the eventual application and commercialisation of innovative new technologies.

To work with the private sector, PUB Singapore has about 150 officers in six technology groups—Intelligent Water Management, Membrane, Network Management, Wastewater Management, Water Treatment, and Water Quality—to help with the transition from fundamental research to test-bedding and pilot- or demonstration-scale studies. They also develop studies to solve or improve daily operational issues. Once the outcomes of these studies are known, the officers consider the implementation of these technologies in PUB's daily operations. In this way, PUB Singapore also acts as a bridge between upstream research and downstream application, adding value to its collaborative partnerships.

In various development schemes run through the EWI office, PUB Singapore is also actively developing human resources to support the nation's rapidly expanding water industry. Researchers with R&D expertise and middle managers are a particular focus. The Visiting Professorship Programme, for example, encourages knowledge transfer from international experts to local researchers. Meanwhile, the graduate scholarship scheme sends researchers overseas to train under prominent experts so that they can bring back their expertise and apply it in Singapore.



PUB collaborates with various partners such as SUEZ Environnement to develop innovative water solutions

Collaborating in R&D

Since the initiation of the current water R&D programme in 2002, some 275 projects—with a total funding commitment of S$148 million—have been successfully seen through to completion. These projects were conducted either in-house, through collaborations, or by test-bedding partners. Many other projects that will improve the sustainability of Singapore's water supply are still underway.

Collaborative research is a key part of Singapore's water technology strategy. With sound expertise in the local water industry and a willingness to share its facilities, PUB Singapore continues to welcome research collaborations that comply with its mission to ensure an adequate, efficient and sustainable water supply for Singapore.

Whether based locally or internationally, opportunities abound for partners in water and its related industries, as well as universities and research institutions. There are also opportunities for creative individuals looking to collaboratively research and develop innovative water technologies. Prospective collaborators simply need to share Singapore's objective of improving water supply management through use-inspired fundamental research, application and technological development, as well as being willing to invest in process improvement, knowledge management and implementation.

PUB Singapore's experience with collaborative R&D demonstrates that collaborative partnerships often result in the transfer of complementary expertise, thus creating a win-win situation for all parties.

Test-bedding opportunities

The water industry's traditionally conservative outlook on new and unproven treatment technologies protects water safety and public health. However, it can also stifle the application of potentially revolutionary water innovations.

Singapore seeks to foster the growth of these innovations by facilitating the testing of products, processes, systems and services. By establishing proven track records, new technologies can become competitive in the water market.

PUB Singapore has many facilities—including waterworks, water reclamation plants, NEWater plants, reservoirs and stormwater canals—that can be made available as industrial test-bedding sites for both public- and private-sector innovators.

Partnering with PUB Singapore attracts external funding

Breakthrough innovations often arise from research that transcends the boundaries of different disciplines. Advancements in polymeric membrane materials, which have greatly benefited seawater desalination and water reuse today, are an excellent example. PUB Singapore encourages such cross-disciplinary research with the potential to lead to high-impact innovations and applications for the water industry.

PUB Singapore will partner with proponents seeking funding support from external agencies even if the research may not relate directly to its operations and expertise. Partnering allows different parties to share the costs of R&D, while reducing associated risks. The funding schemes available in Singapore to support environmental and water research include the Incentive for Research and Innovation Scheme of the Environment & Water Industry Programme Office, the Innovation Development Scheme of the Economic Development Board, the Enterprise Challenge of the Prime Minister's Office, the Innovation for Environment Sustainability fund of the National Environment Agency and the TechPioneer Scheme. PUB Singapore welcomes enquiries from interested parties that can contribute to the delivery of water for all in Singapore.

Singapore's collaborative water research strategy continues to bear fruit, advancing our knowledge of the field and providing practical solutions to the water supply problems confronting Singapore and the rest of the world. Highlights of the some of the country's ongoing research initiatives, demonstrating the diversity and innovativeness of the agency and its collaborators, are presented on pages 14 to 36 of this publication. These projects address all aspects of the water cycle and will contribute to increasing Singapore's water resources, reducing production costs and enhancing water quality and security, while at the same time contributing to the growth of the nation's water industry.

MBR demonstration plant

Membrane bioreactors

A cleaner, more energy efficient and cost-effective way to recycle Singapore's water

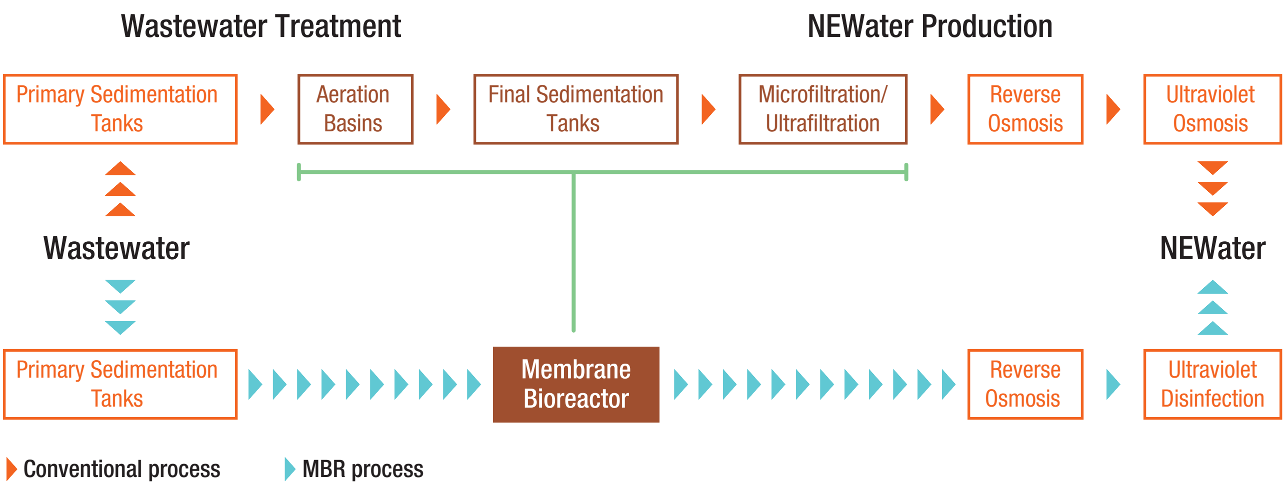
Singapore is set to introduce membrane bioreactor (MBR) technology as a key step to improving the efficiency and reducing the cost of water reclamation efforts. The move represents the culmination of nine years of pilot and demonstration studies as well as full-scale installations spearheaded by PUB Singapore. Plants based on MBR technology are more compact and easier to maintain than conventional systems, while also offering the capacity to process considerably greater volumes of water each day. Facilities employing MBR consistently extract contaminants and impurities from wastewater with the same or greater efficiency than existing infrastructure, reducing energy consumption at these sites and making the process of water renewal more cost-effective and environmentally friendly.

Nearly a third of Singapore's water needs are presently being met by NEWater—wastewater that has been thoroughly processed and purified for both industrial and indirect domestic use. Over the past decade, PUB Singapore has overseen the construction of five NEWater plants in Bedok, Kranji, Seletar, Ulu Pandan and Changi, with the capacity to produce a total of 554,612 cubic metres (m^3) of NEWater each day. However, PUB Singapore has even more ambitious plans for the future, with the aim of expanding its production to meet 50% of Singapore's ever-growing water demand by 2060. As a step towards achieving this goal, the agency is now moving to implement a promising new technology that can deliver purified clean water more efficiently and affordably than previously possible.

In the current generation of wastewater treatment plants, domestic wastewater is initially processed in an aerated bioreactor where it gets mixed with an activated sludge that is rich in bacteria in order to break down the biomass and extract the majority of the nitrogenous waste products. The resulting mixture is then processed in a sedimentation tank that separates solids, and subsequently subjected to microfiltration/ultrafiltration (MF/UF) to further remove particulate matter, bacteria and viruses. Finally, the water is purified through a membrane that blocks the passage of a wide range of contaminants via a process called reverse osmosis (RO). This MF/UF–RO system has proved to be highly effective, but a growing body of evidence suggests that an alternative configuration based on membrane bioreactor (MBR) technology is a better choice for future plants.

"MBR offers many advantages, including robustness and better quality of filtrate, less fouling of the RO membranes and a smaller footprint," explains Harry Seah, director of the PUB Technology and Water Quality Office. Since 2002, PUB Singapore has been conducting extensive assessments of the MBR technology at four water reclamation facilities, and the results obtained have been so encouraging that PUB has now committed to implementing this technology in the future construction of water-reclamation plants and upgrades of existing facilities.

A conventional wastewater treatment plant using activated sludge process



Schematic of the conventional vs MBR process for water reclamation. The MBR process offers smaller footprint, robustness, better filtrate quality, less RO fouling and higher RO fluxes.

Fig. 1: One of three pilot membrane bioreactor pilot units installed at Bedok Water Reclamation Plant in 2003

Fig. 2: PUB personnel inspect an MBR cassette at one of the Bedok pilot plants

Putting MBR to the test

MBR systems advance the streamlining of the wastewater reclamation process by incorporating a more compact aeration tank and eliminating the need for an additional sedimentation tank. The sludge mixture can be either pumped from the bioreactor through an externally placed filtration membrane, or the membrane can be directly submerged within the bioreactor. As a trial run for the technology, PUB Singapore oversaw the construction of a trio of pilot MBR systems at the Bedok Water Reclamation Plant (**Fig. 1**), each of which employed a different type of membrane arranged in some variant of the submerged configuration[1].

Membrane A was composed of sheets containing pores with a diameter of 0.4 micrometres, while Membranes B and C were based on hollow fibres with two different pore sizes (0.4 or 0.035 micrometres, respectively). Each of the three pilot plants was designed to process 300 m^3 of water a day, fed from a common source of settled sewage. The researchers tracked the performance of each setup throughout 2003 and 2004.

All three membrane types performed equally well in terms of the removal of organic contaminants, and in several instances outperformed conventional MF/UF. For example, levels of total organic carbon (TOC), a standard indicator of byproducts from the decay of dead organisms as well as the degradation of pesticides and other chemicals, were consistently about 30% lower following MBR treatment.

As reasonably expected, all three membranes were susceptible to becoming fouled with organic matter, but each had different cleaning demands. Chemical cleaning with bleach and oxalic acid was sufficient to restore Membrane A to full functionality, even after a mechanical failure in the aeration system disrupted the steady of flow of air bubbles that scours the membranes and thereby helps keep them unblocked (**Fig. 2**). The same chemical treatment proved harsh for Membrane B, temporarily removing the outer gel layer that contributes to the extraction of organic carbon, although this layer could be restored during a day of normal operation. Basic maintenance cleaning, however, proved sufficient for Membrane C, which never required intensive chemical treatment throughout the study.

All three membranes steadily delivered output of a quality equivalent or superior to that which could be obtained with MF/UF–RO, and so the investigators further expanded their efforts by exploring the advantages of pairing MBR with RO[2]. Studies performed in the United States had previously demonstrated that this MBR–RO setup can greatly improve the resulting water quality, and these findings were echoed in an additional pilot study conducted at the Bedok facility, which also tested the ability of these membranes to deal with higher rates of liquid flow.

The RO membranes remained intact and largely unclogged when handling MBR-treated water, even at flow rates 30% higher than typically used at existing NEWater facilities. Throughout the study's span from May to October 2004, RO removed more than 98% of the salt content from filtered water, demonstrating that these membranes could reliably perform at the level indicated in the manufacturer's specifications, even during extended periods of heavy use. Indeed, running the system at this higher rate of flux actually improved performance, with a 25% reduction in the concentration of dissolved solids relative to water that had been processed via MBR–RO at the standard flow rate.

In a head-to-head comparison against microfiltration, MBR alone yielded lower concentrations of nitrates, ammonia and TOC. When this MBR output was subsequently processed via RO, the TOC concentration was further reduced; the MBR–RO output contained 24–33 parts per billion (micrograms per litre) of TOC versus 33–53 parts per billion following MF/UF–RO, indicating that the exclusion of contaminants is both more rigorous and more consistent relative to the microfiltration process. This level of performance, paired with the potential for processing considerably greater volumes of wastewater, argued strongly in favour of implementing this model of plant design.

Upscaling to a full-size plant

The next step was to characterise the performance of this approach at a municipal-scale facility through the construction of a full-size MBR–RO system at the Ulu Pandan Water Reclamation Plant. This demonstration system, which was retrofitted into existing plant infrastructure (**Fig. 3**) and put into operation at the end of 2006, was designed to process 23,000 m^3 of wastewater per day. Over the course of the next seven months, the performance of this model plant was assessed with an eye towards optimising its configuration and operation conditions for maximum efficiency[3].

On average, the demonstration plant consumed 12,705 kilowatt hours (kWh) of electricity each day. Approximately 70% of this was being used to power the blowers that move air throughout the system and generate the membrane-scouring flow of bubbles. However, the research team was able to considerably reduce the power consumption of the membrane-scouring blower by simply reducing the aeration time. They further determined that they needed to modify the density of the mixture of wastewater and sludge being processed, which had a strong influence on power consumption and caused energy use to spike even when the level of aeration was low.

This model plant yielded water that was of consistently high quality and more than sufficient for use in the industrial sector, even for manufacturers with a need for ultrapure water. Even after seven months of continuous use, the membranes were in remarkably good condition (**Fig. 4**). The researchers also confirmed that the membrane scouring system was working adequately to prevent the membranes from blocking up.

In a further study at Ulu Pandan, PUB Singapore assessed the performance of a new fibre-based MBR module in a smaller pilot plant (**Fig. 5**) that was operated in parallel with the existing demonstration MBR system[4]. These fibre-based membranes worked reasonably well under typical operating conditions, although they had a notable tendency to become clogged. The researchers concluded that this was at least partly attributable to a design flaw in the membrane modules, which take up liquid only from one side and so are prone to rapid sludge accumulation. The performance of the modules could be improved in the future by reconfiguring them to filter sludge from both sides.

The team generally resolve these clogging problems either by manually wiping the membranes with a sponge or by subjecting modules to routine chemical cleaning, which kept the overall quality of the water output consistently high. The MBR product quality met or exceeded the standards established for water re-use in an industrial setting, indicating that these modules could prove suitable for long-term application if steps, such as membrane air scouring, are taken to mitigate the increased risk of clogging.

Journey to lower energy MBR

In the Bedok pilot studies and the Ulu Pandan demonstration investigations, PUB Singapore has focused its efforts on bolstering energy efficiency[5]. They began at the three pilot plants at Bedok by examining the impact of various measures intended to reduce the cost of operation. The baseline energy usage for these pilot plants was between 1.3 and 1.7 kWh/m^3 of water

Fig. 3: At Ulu Pandan, PUB scientists and engineers oversaw the construction of an MBR tank suitable for processing up to 23,000 m^3 of wastewater per day. From Ref. 3 (© 2008 IWA).

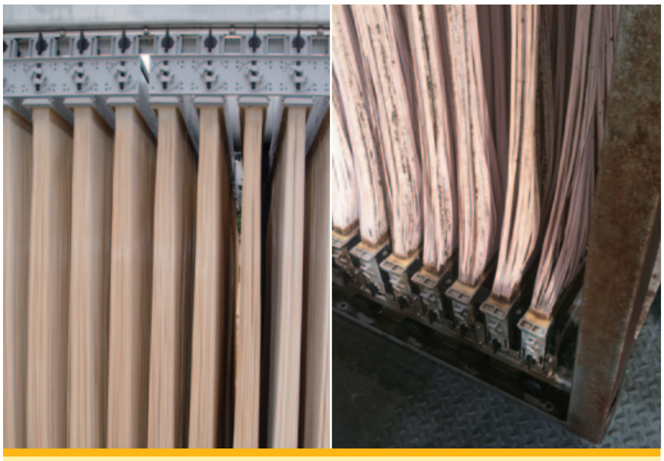


Fig. 4: With regular maintenance and cleaning, MBR cassettes are highly durable. This module (left), which was put into use at the Ulu Pandan was still in good condition after three and a half years (right). From Ref. 3 (© 2008 IWA).

Fig. 5: A miniature pilot MBR plant constructed at the Ulu Pandan facility to test a new membrane module design. From Ref. 4 (© 2009 IWA).

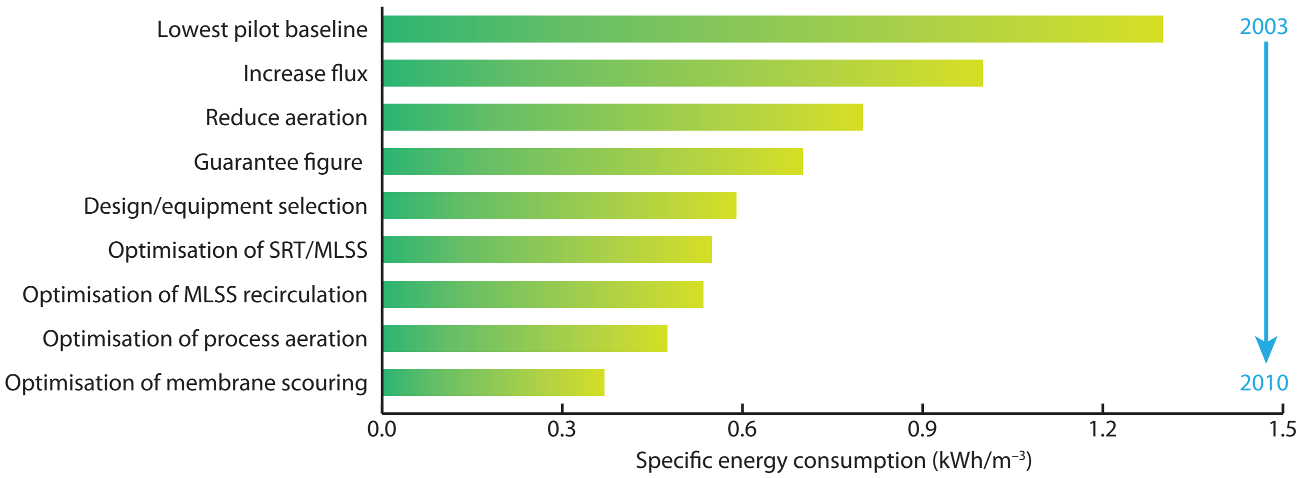


Fig. 6: Progressive reduction in energy consumption of MBR components from the start of the project (1.3 kWh/m^3) to the current optimised operation (0.4 kWh/m^3)

processed. However, by gradually reducing the air supply and increasing the fluid flow rate while maintaining a strict membrane-cleaning regimen, the team was able to reduce power consumption to 0.8–1.1 kWh/m^3. Based on the determination that MBR plants should operate even more efficiently at a larger scale, they set an energy guarantee figure for the Ulu Pandan MBR demonstration plant with the goal of slashing its energy requirements to 0.7 kWh/m^3.

PUB Singapore's efforts in MBR development were an unqualified success, and the final efficiency gains far exceeded their initial expectations. Implementing the same measures applied at Bedok, they achieved further improvements by minimising the amount of solid material contained in the sludge mixture while also reducing the amount of air pumped into the bioreactor by 40%. They also adopted the same regimen of reduced membrane-scouring frequency that had been tested in their initial analysis of the demonstration plant. Ultimately, the application of these refinements at the Ulu Pandan reduced power consumption to a mere 0.37 kWh/m^3—nearly 50% lower than the original target—without having any adverse effect on final water quality or creating the need for a more rigorous membrane cleaning schedule (**Fig. 6**).

Ready for the big time

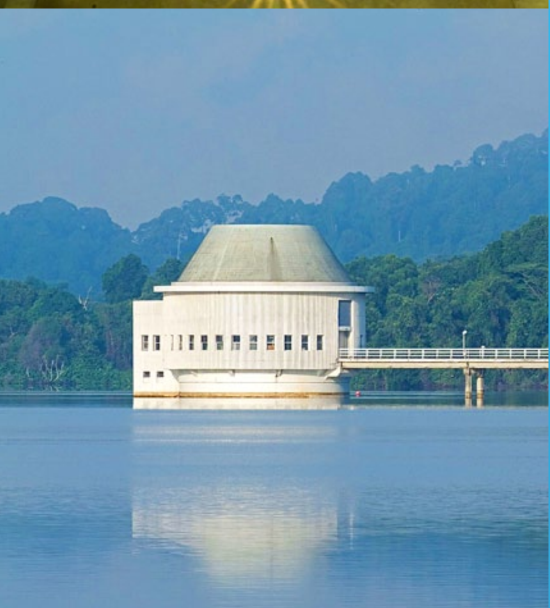
Based on these and other assessments, PUB Singapore has decided to move full speed ahead in implementing MBR technology for Singapore's future NEWater production needs. A number of new MBR-based facilities are now in various stages of completion. These include a plant under construction at Jurong with the capacity to process 68,000 m^3 of wastewater per day. Plans are also underway for a plant at Changi that is capable of handling up to 90,000 m^3 per day as well as a specialised facility that is intended to deal with contaminated industrial water.

"Generally, the existing MF/UF system works fine," comments Seah. "MBR is robust and optimised to reduce energy and cost with greater ease of operation." However, PUB Singapore is continuing to investigate ways to optimise MBR performance, and currently has 20 different MBR-related test studies and pilot projects in the works. Other nations are also hoping to benefit from the expertise acquired in this process. PUB scientists and engineers are presently assisting in the design of what will be the world's largest MBR plant, a 100,000 m^3-capacity facility slated for construction in Beijing, China.

Currently, the majority of NEWater is being processed for commercial and industrial use, most notably to meet the heavy demands of plants engaged in semiconductor wafer fabrication. However, the high purity achieved by this process also makes it safe for domestic use, and PUB Singapore is keen to increase public awareness of the versatility of this reclaimed water. "Roughly two percent of NEWater is injected into public reservoirs, where the water will go through the natural and normal water treatment process again," says Seah. "This is partly for public education purposes, and to help people to overcome their psychological barriers with regard to water reclamation processing."

References

1. Tao, G., Kekre, K., Wei, Z., Lee, T.C., Viswanath, B. & Seah, H. Membrane bioreactors for water reclamation. *Water Science & Technology* **51**, 431–440 (2005).
2. Qin, J.-J., Kekre, K.A., Tao, G., Oo, M.H., Wai, M.N., Lee, T.C., Viswanath, B. & Seah, H. New option of MBR-RO process for production of NEWater from domestic sewage. *Journal of Membrane Science* **272**, 70–77 (2006).
3. Tao, G., Kekre, K., Viswanath, B., Oo, M.H. & Seah, H. Membrane bioreactor for water reclamation in Singapore. *Water Practice & Technology* **3** (2008).
4. Qin, J.-J., Oo, M.H., Tao, G., Kekre, K.A. & Hashimoto, T. Pilot study of a submerged bioreactor for water reclamation. *Water Science Technology* **60**, 3269–3274 (2009).
5. Tao, G., Kekre, K., Oo, M.H., Viswanath, V., Aliman, M.D.Y. & Seah, H. Energy reduction and optimization in membrane bioreactor systems. *Water Practice & Technology* **5** (2010).



Intelligent Watershed Management

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

Forecasting reservoir water quality

The development of computer models to simulate water quality in Singapore's catchments and reservoirs will help improve catchment and reservoir management

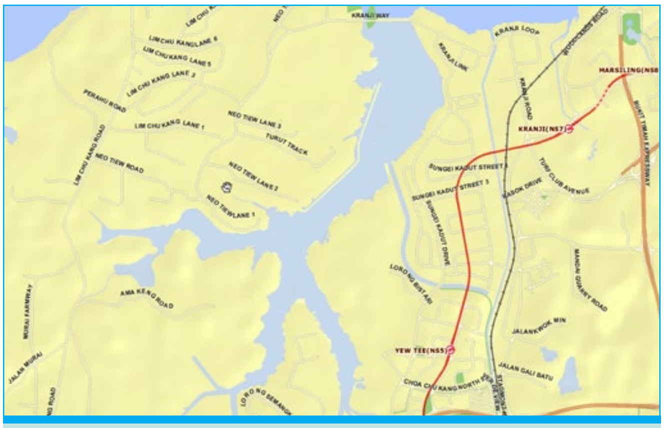


Fig. 1: Land-use map of Kranji reservoir catchment

Fig. 2: The moored reservoir monitoring station houses high-resolution instruments for measuring environmental variables

A computer model that simulates the water quality of Singapore's Kranji reservoir has been developed by a research team led by Edmond Lo of Nanyang Technological University (NTU).

"Our model will help managers predict water quality changes in existing reservoirs and plan for the effects of future environmental perturbations such as land-use changes," says Lo.

To monitor rainfall and predict inputs to the reservoir following storm events, Lo and his collaborators from NTU and PUB Singapore established a series of gauging stations in the surrounding catchment (Fig. 1). This allowed them to analyse water samples for nutrients, suspended solids and bacteria. They used these data to develop a catchment model that simulates flow and nutrient inputs based on measured rainfall.

"The catchment model performed very well with the simulation results agreeing with measurements of flow based on hydrograph recordings," Lo notes.

The researchers also used moored instruments (Fig. 2) to measure water quality variables such as water temperature, conductivity and dissolved oxygen levels in the reservoir itself, as well as meteorological variables. Experiments conducted in NTU's laboratories complemented these measurements. Other experiments measured oxygen usage by organisms in reservoir sediments and the flux of nutrients such as phosphate, nitrate and ammonia between the sediments and the overlying water column. Lo and his colleagues also identified which nutrients limited algal growth within the reservoir.

"We used data from the instruments in the reservoir and our laboratory studies to calibrate our three-dimensional, integrated mathematical model of reservoir water quality," explains Lo.

The reservoir water quality model was originally developed at the University of Western Australia's Centre for Water Research (CWR). In collaboration with CWR researchers, the Singapore-based team adapted the reservoir water quality model for Kranji. The model has two components: a hydrodynamic module that predicts flow velocities and current directions, and a water quality module that simulates the dynamics of nutrients and algae within the reservoir.

The researchers fed the output of the catchment model into the calibrated reservoir water quality model to simulate water quality in the reservoir. They found that the simulated levels of suspended solids, algal growth and other parameters agreed reasonably well with actual measurements of water quality at times of episodic increases in nutrient levels caused by major storms.

"The model can form the basis of an in-house capability to better predict water quality in Singapore's reservoirs now and in the future," concludes Lo.

Researchers and affiliations

E.Y.M. Lo,* L.H.C. Chua,* E.B. Shuy and K.Y.H. Gin†
Nanyang Technological University, Singapore
†Present affiliation: National University of Singapore

J. Imberger and J. Antenucci
Centre for Water Research,
University of Western Australia

Y.K. Chiam-Tai, H. Eikaas, T.K. Meng
PUB Singapore

Contacts

cymlo@ntu.edu.sg
chcchua@ntu.edu.sg

Keeping water safe to drink

Tropical reservoir management gets a boost from an early-warning system that forecasts harmful algal blooms

Fig. 1: The Upper Peirce Reservoir, Singapore

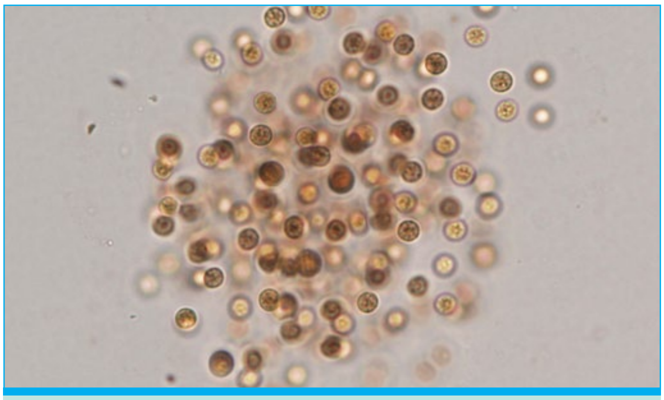


Fig. 2: In high numbers, the cyanobacterium *M. aeruginosa* can turn water supplies toxic

A major drinking water resource of Singapore—the Upper Peirce Reservoir (Fig. 1)— occassionally experiences problems with blue-green algae called cyanobacteria (Fig. 2). Blooms of cyanobacteria not only cause unsightly scum, but also produce toxins ('cyanotoxins') that could potentially contaminate drinking water and pose a serious hazard to human health.

"Understanding the factors that trigger blooms of cyanobacteria is an important first step in controlling and eventually eliminating the problem at the source," explains Rajasekhar Balasubramanian of the National University of Singapore (NUS).

Balasubramanian is the principal investigator of a four-year multidisciplinary programme designed to understand fluctuations in the water quality of tropical reservoirs. The programme includes researchers from the NUS, the Singapore–Delft Water Alliance and Netherlands-based Deltares , working in partnership with PUB Singapore. The research also involves collaborations with other universities and international research organisations and industries.

"Our study focuses on the Upper Peirce Reservoir, which is used for recreational purposes as well as being an important source of drinking water," Balasubramanian explains.

The researchers have already developed a variety of innovative analytical methods to detect and routinely monitor pollutants and contaminants in reservoir water and sediments. They also use state-of-the-art molecular and analytical techniques to screen for cyanobacteria and their toxins, as well as conducting toxicological tests on contaminants found in water samples.

One cause of cyanobacterial growth is the excessive build-up of nutrients in the reservoir resulting from inputs from the surrounding catchment areas, a process known as eutrophication. The researchers therefore instigated studies of nutrient levels in the rainfall runoff entering the reservoir.

To understand the process more thoroughly, Balasubramanian and his colleagues are developing a comprehensive eutrophication model that will allow present and future environmental conditions in the reservoir to be simulated. The model already incorporates information on water quality and nutrient levels. It also takes into account sediment processes such as the recycling of nutrients and trace elements between the sediments and the overlying water column.

In addition to the studies of cell buoyancy and bloom dynamics needed to validate the model, the researchers are exploring the use of remote sensing to monitor bloom events and to assess other water quality issues. "Our aim is to develop an advanced early-warning system for forecasting cyanobacterial bloom events that will help in the management of water quality in the Upper Peirce Reservoir and other similar tropical reservoirs," says Balasubramanian.

To further bolster their armoury against cyanobacteria, the researchers have developed a low-cost non-harmful technology that removes cyanotoxins from contaminated waters.

Researchers and affiliations

R. Balasubramanian*
National University of Singapore

D. Burger
Deltares, The Netherlands

H. Eikaas
PUB Singapore

Contacts

eserbala@nus.edu.sg

On-the-spot reporters of stream health

Surveys of the insects and invertebrates that live in Singapore's waterways complete the picture of stream health

Fig. 1: The Protected Central Catchment (green shading) is located in the centre of Singapore's main island. The red dots indicate study sites, including 33 concrete canals and 24 forested waterways within the central catchment.

Singapore has added a biologically based water quality index to its tools for monitoring the health of its streams and waterways. A research team led by Tanya Blakely and Jon Harding of the University of Canterbury, New Zealand, developed the index in conjunction with PUB Singapore.

"The 'SingScore index' is designed to assess the ecological health of Singapore's natural and urbanised streams, and will help identify appropriate management," says Harding.

Many of Singapore's waterways are affected by urbanisation, resulting in deteriorating water quality. The chemical analyses historically used to assess water quality are expensive and time consuming, and provide only a snapshot of environmental condition. In contrast, the presence or absence of aquatic invertebrate species can paint a longer-term picture of stream health: different species have different tolerances to pollutants.

Blakely and Harding surveyed the chemical, physical and biological characteristics of nearly 50 waterways on Singapore's main island (Fig. 1). These waterways ranged from unprotected canals in urban environments to waterways running through the protected central catchment.

"By studying the invertebrate communities in waterways along the entire natural–urbanised gradient, we were able to determine the relationship between invertebrate community composition and prevailing environmental conditions," explains Blakely.

Blakely and Harding collected over 59,000 invertebrates belonging to 74 species, including insect larvae, snails and worms (Fig. 2). Some of these species were highly tolerant to pollution, while others were more sensitive and can be indicative of good water quality.

After scoring each species for its ability to tolerate pollutants on a 10-point scale, with those species scored 10 being the most sensitive, the researchers summed the tolerance scores for all species found at a site, divided by the number of species present, and multiplied by 20 to give the 200-point SingScore index of water quality.

Through this study, they found that many of Singapore's urban waterways have an index score of 79 or less, indicating poor water quality. However, most of the waterways in the central catchment have very good or excellent water quality, with index scores over 100. This is important because waterways within the central catchment are tributaries of four of Singapore's largest drinking water reservoirs.

"Our index will help PUB monitor the long-term health of Singapore's waterways and assess the effects of stream restoration schemes," concludes Blakely.

Stephen Moore, Landcare Research, New Zealand

Fig. 2: A selection of aquatic invertebrates surveyed during the study

Researchers and affiliations

T. Blakely* and J. Harding*
University of Canterbury, New Zealand

H. Eikaas
PUB Singapore

Contacts

anya.blakely@gmail.com
jon.harding@canterbury.ac.nz

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 wastewater using physico-chemical processes, the technology has grown and developed and is now an indispensible part of Singapore's water strategy.

The NEWater demonstration plant, commissioned in May 2000, used microfiltration, reverse osmosis and finally ultraviolet disinfection to produce reclaimed water from secondary effluent. The quality of the reclaimed water—branded 'NEWater'—surpasses the drinking-water standards laid down by the US Environmental Protection Agency and the World Health Organization.

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

Less fouling filtration

Flat ceramic membranes eliminate sludge accumulation in a pilot plant for wastewater treatment

New ceramic membrane filters that produce high-purity water in a small-scale wastewater treatment plant in Singapore will be an alternative to polymeric membranes in the membrane bioreactor-based processes of larger plants. A research team led by Terutake Niwa and Akira Oishi of Meiden Singapore developed the flat sheets of ceramic filters (Fig. 1) in close collaboration with PUB Singapore.

Processes based on membrane bioreactor (MBR) technology are generally an energy-efficient and cost-effective way to clean and purify municipal wastewater because they combine biochemically active substances, which react with water-soluble contaminants, with high-performance filtration systems that remove materials insoluble in water. However, the accumulation of ultrafine solid particles generated by the biochemical reactions can block the flow of clean water and increase pressure across the membrane.

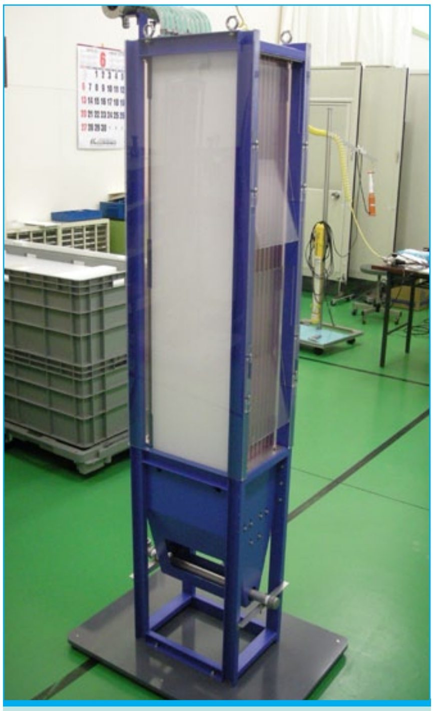


Fig. 1: A ceramic membrane module

Oishi notes that the flat surface of the filters eliminates build-up sites thereby providing inbuilt antifouling properties.

Conventional polymer ultrafiltration membranes tend to break easily under high pressure and degrade when exposed to chemicals or heat. In contrast, ceramic membranes display high chemical and thermal resistance. The team also expects the ceramic membranes to be much tougher against scratching than conventional systems.

The researchers completed successful preliminary laboratory tests using the ceramic filters to purify wastewater samples in 2009 at the Ulu Pandan Water Reclamation Plant. Drawing on their results, they designed an MBR pilot plant equipped with the ceramic filters to test them on a larger scale.

In the pilot plant (Fig. 2), the researchers first filtered out large objects. They then subjected the pre-settled wastewater to bacteria-mediated reactions in an oxygen-free environment in order to reduce nitrogen and phosphorous concentrations. Next, the wastewater entered an oxygenated or aerobic tank containing the ceramic membranes. There, the wastewater underwent further biochemical reactions before passing through the filter as permeate water.

Oishi's team observed that the ultrasmall pores of the membrane could completely separate suspended solids from the permeate water. Moreover, they found that when the buildup of sludge on the membrane caused the trans-membrane pressure to peak, maintenance cleaning progressively restored the pressure. This demonstrated the continuity and stability of the MBR system for long-term operation.

The researchers are continuing the pilot tests with on-line maintenance chemical cleaning for long-term commercial use. They are also planning to apply their ceramic membrane to water treatment in other tropical countries.

Researchers and affiliations

T. Niwa and A. Oishi*
Meiden Singapore

K. Kekre, G.H. Tao and H. Lie
PUB Singapore

Contacts

oishi.a@meidensg.com.sg

Fig. 2: The ceramic MBR pilot plant

Giving oil the slip

The development of an oil-resistant membrane distillation system eliminates problems caused by oil droplets in a novel desalination process

Removing the salt from seawater is an attractive option for water-scarce countries looking to increase their freshwater supplies. Desalination usually involves driving seawater through a salt-rejecting porous membrane, but these membranes can be damaged or even destroyed by the impurities often found in marine waters, such as oil. PUB Singapore is currently working with researchers at Nanyang Technological University and a desalination technology company, memsys clearwater, to develop membranes that repel oil droplets in water.

Specialising in a type of desalination called vacuum multi-effect membrane distillation (V-MEMD), memsys has produced systems that promise to be more energy-efficient than more conventional desalination technologies. In a V-MEMD system, seawater is warmed to produce water vapour, which is then drawn through the membrane by lowering pressure on the far side. Once through the membrane, the water vapour is condensed and collected. Because the system operates at relatively low temperatures of 50–70 °C, waste heat from factories or power plants, or energy from the sun, can be used to drive it. At the Marina Barrage in Singapore, memsys is currently pilot-testing a small solar-powered vacuum membrane distillation (MD) system (Fig. 1).

Fig. 1: The memsys desalination system is resistant to damage from oil in water

For water vapour to pass through the membrane efficiently, a phenomenon called 'wetting'—the accumulation of liquid water within the membrane—must be avoided, says Kui Zhao, a researcher at memsys. "The MD membrane is a hydrophobic membrane that only allows gases or water vapour to pass," he explains. "Wetting means the membrane is losing its hydrophobic property and distillation function." Wetting is more likely if oil in the seawater sticks to the membrane.

Zhao and his colleagues tested whether or not this issue could be avoided by making the membrane more oil resistant, or oleophobic. They assessed a number of membranes, including some commercial membranes to which they applied an oleophobic coating. The membranes were tested for their permeability as well as for oil resistance.

The oleophobic coating successfully improved the oil-resistance of the membranes. Furthermore, the oleophobic properties of the membrane had another benefit. "Besides oil-resistance, the oleophobic membrane is also more water-resistant than the normal hydrophobic membrane," Zhao explains. That means the membrane is even less prone to wetting.

Having assessed which of the oleophobic membranes performed the best, the next step will be to further test the best one in a commercial-scale system, Zhao says—a process that should be completed by October 2011.

Researchers and affiliations

K. Zhao, G.J. van Gendt, W. Heinzl, G. Lange*, Y. Singh, W. Htut and R. Wang
memsys clearwater, Singapore

T. Fane
Singapore Membrane Technology Centre, Nanyang Technological University, Singapore

Contacts

goetz.lange@memsys.eu

Making every drop count

Almost all of Singapore's land area could serve as a rainwater catchment thanks to a treatment plant that can efficiently process both rain and seawater

Fig. 1: The variable salinity process enables treatment of both brackish and seawater at the same facility, allowing the catchment area to increase to more than 90% of Singapore's land area.

Providing water to meet the needs of Singapore's five million inhabitants is a challenging task. With every major estuary already dammed into reservoirs, and networks of rainwater catchment canals established over much of the island city (Fig. 1), Singapore has turned to tapping the minor streams and rivulets on the island's periphery that swell after each stormy downpour. With little room to build catchment structures in these areas, however, treatment plants need to be located on-site—an inefficient proposition unless they can operate continuously.

A team at PUB Singapore has patented a new 'variable salinity plant' and designed a demonstration plant that can economically harvest surface runoff from these estuarine regions. The dual-mode plant, which can desalt seawater when the rainwater catchment canals are empty, could expand catchment systems from some 66% to over 90% of the island's land area.

"The variable salinity plant is the first of its kind in the world," says Sarah Hiong, one of the team's engineers. "The main challenge in its design was to construct a robust plant that can operate reliably for a long period of time, and can produce drinking water from seawater and brackish water at an affordable cost."

Purifying water with varying salt content requires a membrane plant that can controllably handle wide ranges of operating pressures. When the plant is treating rainwater runoff, the feed pressure to the reverse osmosis membranes is only about 0.7 MPa. But when treating seawater, the feed pressure can be as high as 5 MPa. By implementing a control process that allows uninterrupted switching between canal water and seawater modes, the technology ensures high plant utilisation.

Once pumped into the plant, water purification takes place in four stages. Perforated screens filter large objects from the stream, and then microfiltration membranes remove any particle bigger than 0.1 µm. Next, reverse osmosis membranes desalt the water. In seawater mode, the stream passes through seawater reverse osmosis (SWRO) membranes before further salt removal with brackish water reverse osmosis (BWRO) membranes. In canal water mode, both the SWRO and BWRO membranes can operate in parallel, owing to the low salt content. Following final disinfection and pH adjustment, the cleansed water exits the plant via distribution pipelines.

Hiong notes that because the variable salinity plant is cheaper and consumes less energy than seawater desalination, this technology could be applied worldwide and benefit water-stressed estuarine regions in the near future.

Researchers and affiliations

H. Seah, S. C. Chua, K. L. Khoo, J. Y. Chua, C. W. Toh and S. Hiong*
PUB Singapore

Contacts

sarah_hiong@pub.gov.sg

Network Management

Singapore's water strategy focuses on the management of water resources in an integrated manner at all points of the water loop.

A key aim of water research and development in Singapore in the field of network management is to ensure the delivery of high-quality water from the waterworks to consumers while ensuring the collection and reclamation of wastewater in an effective and efficient manner.

The management and maintenance of Singapore's networks is therefore a critical function in the economic and social life of Singapore, as well as a solemn responsibility that spurs Singapore's water researchers to even greater technological innovation.

Lighting the way to better water quality

Optical sensors that instantly detect contaminants by monitoring the refractive properties of water are set to enhance water quality monitoring in Singapore

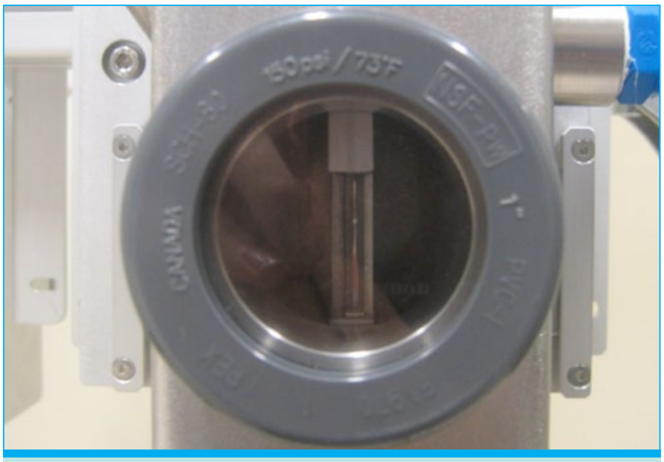


Fig. 1: The laser-based sensor cell of the EventLab networked water quality monitoring system

Fig. 2: An EventLab installation in Singapore

Contaminated drinking water supplies can pose a significant threat to public health and national economies. Water utilities such as PUB Singapore are therefore eager to employ cost-effective, cutting-edge methods to continually monitor water quality at all stages of collection and delivery.

With a view to establishing an early-warning system for Singapore's water supply, a networked monitoring system called EventLab, which instantly detects contaminants by recording how water affects laser light, has been developed by researchers from Optiqua Technologies in Singapore working in collaboration with PUB Singapore and Vitens, the largest drinking-water supply company in the Netherlands.

"Statistics show that 30–60% of water quality incidents around the world, such as water discolouration or the backflow of untreated water, originate in the water distribution network," says Melchior van Wijlen, managing director of Optiqua Technologies. Contamination events are often reported by consumers, he explains, but action by a provider can sometimes take days. Identifying the source and extent of contaminations can also be difficult, which leaves the public exposed.

The researchers believe that EventLab provides a unique, cost-effective solution to this problem, particularly as it monitors the full spectrum of contaminants, unlike traditional sensors such as those monitoring pH or conductivity. The system works on the concept that any substance dissolved in water will affect the water's refractive index—a factor related to the speed of light in the water.

"Refractive index is a useful generic indicator of water quality because any substance, when dissolved in water, will change the refractive index of the water matrix," explains van Wijlen. In an EventLab sensor (Fig. 1), laser light passes close to the sample, experiencing a phase shift that can be related to the contents of the water.

To distinguish harmful from non-harmful contamination events, the research team conducted extensive tests on their sensors under conditions that imitated real water contamination events. Based on their results, the team designed event-detection algorithms that identify contaminants against a background of harmless natural variations in water. This means that the sensors can effectively detect contaminants at very small concentrations, far below those that would be expected to induce serious health effects, van Wijlen notes.

EventLab has been tested and validated in pilot projects in Singapore (Fig. 2) and the Netherlands as an effective method for real-time water quality monitoring. As a next step, Optiqua and PUB Singapore are exploring the possibilities of deploying a network of Optiqua's newest EventLab sensors, which will show improved accuracy over previous models in combination with further optimised event-detection algorithms and software.

Researchers and affiliations

M. van Wijlen*
Optiqua Technologies, Singapore

R.J. Xie and A.N. Puah
PUB Singapore

Contacts

melchior.van.wijlen@optiqua.com

Sensing water distribution problems

A network of wireless sensors will alert managers to hiccups in Singapore's water supply

Fig. 1: Singapore's central business district is now home to a network of wireless sensors that continually monitor the water distribution system

Fig. 2: Emulation of a burst water main was quickly detected by a neighbouring sensor node of Singapore's prototype monitoring network

A prototype network of 25 sensor packages that report in real time on water pressure, flow rate and disinfectant levels has been installed in Singapore's central business district (Fig. 1). Encouraging results on the long-term accuracy of the sensors and the ability of the network to locate pipe bursts have been obtained during the trial. Enhancements to the system are underway and, once fully developed, will automate monitoring of water quality deviations and leaks in Singapore's entire water distribution system.

PUB Singapore and the Massachusetts Institute of Technology (MIT) are developing, testing and implementing the low-cost system in collaboration with the Center for Environmental Sensing and Modeling as part of the Singapore–MIT Alliance for Research and Technology programme. Solar panels or the street lighting system can be used to power the packages directly.

The idea, according to Harry Seah, director of PUB Singapore's Technology and Water Quality Office, is to develop a more efficient and reliable detection system that will serve as an early-warning, event-locating and water-demand prediction system. Successful development of the full system will make it of great commercial value.

The packages of sensors, which include acoustic hydrophones, extend about 10 cm into distribution pipes of least 20 cm in diameter. The sensors measure water pressure, water flow, conductivity, pH and oxidation–reduction potential (ORP). Transient changes in pressure for example, caused by a leak or burst pipe, arrive at and are sent from different sensors at different times depending on sensor location. A central computer receives the automatic reports from the sensors via the 3G mobile phone system. The computer then integrates all the real-time hydraulic data into a model of the water distribution system that was established using EPAnet simulation software from the US Environmental Protection Agency.

The model can localise the problem to within an average of about 40 m and send out an alarm. Last year, the development team tested the system using fire hydrants to simulate burst water mains (Fig. 2). A new round of experimentation integrating both acoustics and pressure is already underway.

Deviations in the quality of the water supply are detected by the ORP and pH sensors that provide a measure of disinfectant levels, such as the concentration of chlorine. Water quality issues can be localised in the same way as leakages.

As the wireless sensor network is developed and tested further, it will gradually be implemented throughout the water distribution network in Singapore.

Researchers and affiliations

A. Whittle, A. Preis and M. Allen
Center for Environmental Sensing and Modeling
Singapore–MIT Alliance for Research and Technology

T. Soh, C.P. Teo, J. Lau and R.J. Xie*
PUB Singapore

Contacts

xie_rongjing@pub.gov.sg

Metering water flow and sediment load

A hybrid meter using two ultrasound-based methods for measuring water flow and sediment transport in pipes is being developed for the water industry

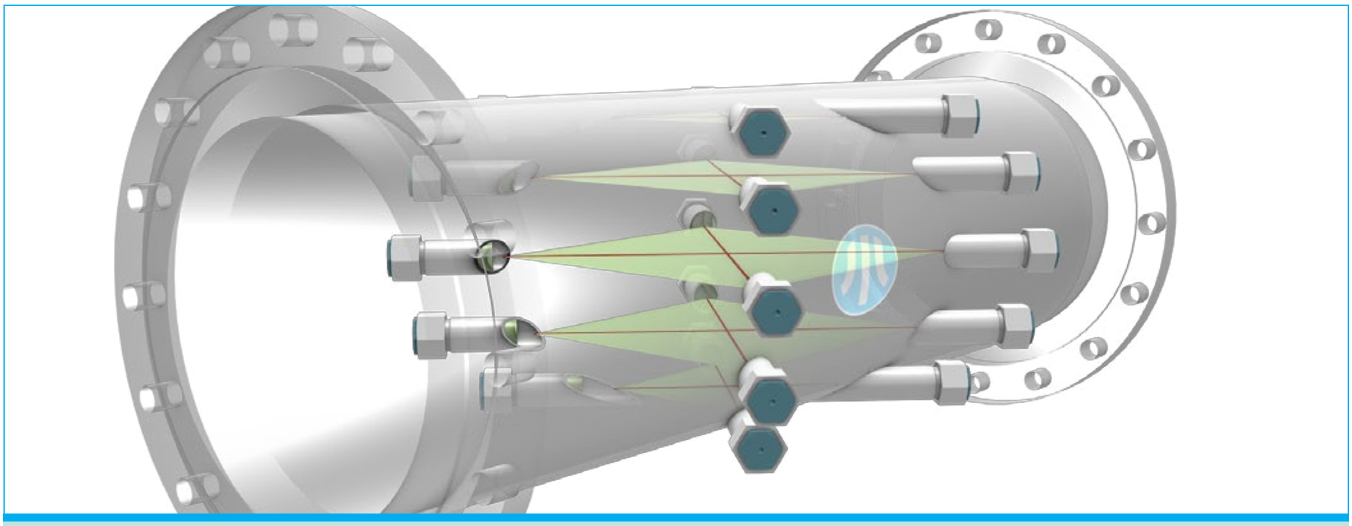


Fig. 1: A flow meter based on time-of-flight measurement and a calibration-free sediment meter based on multifrequency ultrasound backscattering

To monitor and optimise processes in water and treatment plants, the water industry needs accurate, reliable and cost-effective ways of measuring water flow and the transport of high concentrations of suspended sediments in complex pipe systems. Working in conjunction with PUB Singapore, a team of scientists and engineers led by Thomas Hies of DHI Water & Environment in Singapore and involving collaborators from HydroVision in Germany is developing a new acoustic-based mass-meter device capable of accurately measuring water flow and suspended sediments simultaneously.

"The existing water-monitoring methods used by the water industry to collect data on the concentration of sediments moving through in pipes are relatively expensive and labour intensive, demanding a lot of intrusive hands-on maintenance," explains Hies. "In addition, because water flow and sediment transport within complex pipe systems vary a great deal from place to place and over time, the accuracy of measurements can be difficult to assess, meaning that the measurement instruments have to be regularly accessed for calibration purposes."

Ideally, devices designed to gather high-quality data on water flow and sediment fluxes in pipes should be easy to use, accurate, reliable and cheap to install and maintain. To meet these needs, Hies and his team turned to ultrasound technology. "Ultrasound-based devices can be left in place to gather reliable data automatically without the need for regular intrusive maintenance and calibration to ensure accuracy, making ultrasound the technology of choice for applications in the water industry," says Hies.

The automated, acoustic mass meter being developed by the team will comprise two improved methods to measure water flow and the concentration of suspended sediment particles with high precision (Fig. 1). One subsystem is a flow meter, which very accurately measures flow velocity based on time taken to pass through the instrument. The other subsystem is a calibration-free sediment meter, which uses the backscattering of ultrasound from sediment particles in the water. "Ultrasound frequencies interact differently with suspended particles differing in size and consistency, as our experiments and simulations have shown," explains Hies.

By combining the two principles, the hybrid instrument should be able to reliably determine the absolute mass of sediment passing through the pipe with a high degree of accuracy. Although designed primarily for use in the water industry, the acoustic mass meter could also find applications in power plants, the food industry and in the monitoring of sediment transport in rivers, dams and ports caused either naturally or by disturbances.

Researchers and affiliations

T. Hies,* S. Leschka, L. Yanyan, L. Jian and N.C. Huat
DHI Water & Environment, Singapore

J. Skripalle, M. Haug and R. Nell
HydroVision, Germany

Contacts

thi@dhi.com.sg



Wastewater Treatment

Singapore's research and development in wastewater treatment focuses on closing the water loop to short-circuit the water cycle. Instead of discharging treated wastewater 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 wastewater and distributing it for large-scale non-potable use by industry as well as for indirect potable use.

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

Fresher air for Singapore's wastewater treatment

Harnessing the odour-eating powers of microbes in a cleverly designed biocarbon tower efficiently removes odorous chemicals from sewage gases

Fig. 1: A view of the biocarbon tower that is removing sewage gas odours at the Kranji Water Reclamation Plant

Fig. 2: Overview of the Kranji Water Reclamation Plant

Odorous gases from sewage at a wastewater treatment plant in Singapore are being neutralised by a biocarbon tower (Fig. 1). Developed and operated by Lawrence Koe and colleagues from Aromatrix in Australia, working in partnership with PUB Singapore, the tower is located at the Kranji Water Reclamation Plant (Fig. 2).

Sewage gases contain odorous chemicals such as hydrogen sulphide, which smells of rotten eggs. Removing these gases is important for improving air quality and the working and living environment in and around the treatment plant.

"Our biocarbon tower uses biologically activated carbon seeded with microorganisms to remove odorous chemicals from sewage gases and is the first and only one of its kind in operation," says Koe.

Many microorganisms perform useful functions that can benefit the environment. The biocarbon tower developed by Koe and his colleagues uses specially selected microorganisms already existing in wastewater effluent. These microorganisms are immobilised on a porous matrix of activated carbon packed within the treatment tower. Through their metabolic activity, they can consume odorous sewage chemicals, converting them into innocuous products that have a non-offensive odour.

"Sewage gases delivered to the biocarbon tower are absorbed by the activated carbon and efficiently degraded by microorganisms," explains Koe. "If, after exiting the tower, the air requires further treatment it can be passed back through the tower, but generally speaking it is usually clean enough to be discharged into the environment after just one treatment."

The design of the biocarbon tower makes it efficient. Its activated carbon is highly porous, with a large surface area on which the microorganisms can live, multiply and consume odorous gases. As a result, large volumes of sewage gases can be processed quickly.

The system is robust and easy to operate. "Effluent water or nutrient solution is intermittently flushed through the tower to keep the microorganisms alive and healthy and to wash away bioreaction products from the activated carbon so that it can be used again without needing to be replenished," notes Koe. "Other than that, very little maintenance is required."

Koe and his collaborators found that the treatment tower removes up to 99% of incoming hydrogen sulphide and other malodourous chemicals under current operating conditions. "We are now looking at ways of improving the system even further by identifying optimal operating modes for consistent performance under a range of sewage conditions, and by investigating different grades and types of biocarbon medium for increased efficiency," says Koe.

Researchers and affiliations

L. Koe* and Y.Y. Loo
Aromatrix, Australia

Y.L. Wah
PUB Singapore

Contacts

ccckoe@gmail.com

Reclaiming water more sustainably

Battery-like technology increases NEWater plant water recovery to over 90%

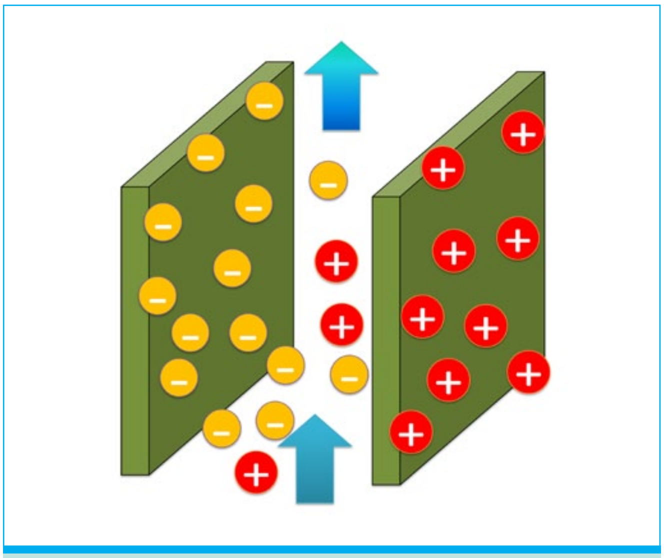


Fig. 1: In capacitive deionisation technology, salt and other ions (spheres) are separated from a stream of brine water by an electric field between two electrodes

Fig. 2: A pilot plant uses a CDI-based system to recover much more clean water from waste sources than existing treatment plants

Reverse osmosis (RO) membranes are at the heart of water reclamation plants worldwide because they can separate out harmful contaminants. However, while squeezing water through RO filters cleans most of the influent stream, a significant fraction remains behind as a brine solution filled with heavy metals, salt and other ions, as well as organic compounds. At the NEWater factories in Singapore, for example, more than 20% of the treated water becomes brackish waste.

Jian Jun Qin and colleagues from PUB Singapore and the National University of Singapore have developed a pilot system to make water reclamation systems more sustainable. By cleansing waste brine with a combination of filters and a technology called capacitive deionisation (CDI), the team has found a way to boost water recovery rates at the NEWater factories from 75% to over 90%.

CDI technology is a chemical-free way of desalinating water using a microscopic phenomenon known as electric double-layer capacitance. When a thin electrode is charged and dipped into an electrolyte solution, oppositely charged ions spontaneously stick to it in a distinct layer. Making a stream of waste brine water flow between a pair of large, porous electrodes with positive and negative charges therefore enables rapid removal of nearly all the ions (Fig. 1).

One of CDI's unique advantages, according to Qin, is that the energy required for the process can be further lowered if the electric power can be regenerated after the brine desalination is complete. Controllably releasing the stored charge, or capacitance, from the thin electrodes produces enough electricity to offset most of the energy used in the original desalination process.

Qin and his colleagues have also investigated problems with fouling of the CDI electrode surface that can make the device fail prematurely. They developed a pilot system (Fig. 2) with biologically activated carbon filters to remove some of the total organic content within the RO brine before passing the stream into the CDI unit.

After a final RO polishing of the CDI effluent, the quality of the water produced by the CDI pilot plant is equivalent to, or better than, NEWater. The team is further optimising the operations of the CDI pilot system and targeting up to 95% NEWater plant water recovery if the CDI-based water recovery system is incorporated into existing NEWater factories.

Researchers and affiliations

J.J. Qin,* G.H. Tao, B. Viswanath, K. Kekre and H. Seah
PUB Singapore

H.Y. Ng, L.Y. Lee, H.Y. Ng and S.L. Ong
National University of Singapore

Contacts

qin_jianjun@pub.gov.sg

A sound solution for waste reduction

Blasts of high-frequency sound waves boost the speed and efficiency of sludge processing at a pilot plant in Singapore

Much of the hard work involved in the digestion of sludge is done by bacteria that consume and break down organic materials to produce methane and carbon dioxide , which can in turn be repurposed for use as fuel. However, a considerable amount of material remains undigested after this process, and removing the byproducts requires additional time and energy.

"In Singapore, digested sludge is first dewatered and then transported to an incineration facility," explains Wah Yuen Long, director of PUB Singapore's Water Reclamation Department.

Wah's department has explored the benefits of implementing ultrasonic disintegration technology as a means for reducing solid waste output arising from the water reclamation process[1]. Ultrasonic systems employ high-frequency sound to break down biological cells in untreated sludge, so that bacteria find it easier to subsequently digest and metabolise cell contents. "Ultrasonic technology can increase biogas production and reduce the amount of sludge solids for disposal," explains Wah.

As a test, they constructed a pilot ultrasonic facility at Singapore's Ulu Pandan Water Reclamation Plant. The pilot facility is capable of processing up to 200 m^3 of thickened sludge per day. The sludge was processed in a specialised reactor containing five sets of the ultrasonic disintegration apparatus (Fig. 1), and then transferred to an anaerobic digester for microbial processing. For the purposes of comparison, a parallel 'control' stream of sludge was delivered directly to another similar digester tank without any ultrasonic treatment.

The extra step of processing made a noticeable difference, yielding an average 35% increase in biogas output over the course of the nine-month study (Fig. 2). The composition of the resulting gas mixture was indistinguishable from that produced by the control tank, indicating that ultrasonic disintegration allowed the standard biological processes to proceed more rapidly and efficiently. The researchers concluded that implementation of the technology could improve the removal of solid waste by 20–30%. "If implemented fully and operated successfully at all of PUB's water reclamation plants, we anticipate that ultrasonic disintegration could eliminate about 200 tonnes of dewatered sludge daily," notes Wah.

These improvements in efficiency could reduce the need to invest in additional digesters at plants while also boosting overall fuel output. Accordingly, PUB Singapore is now moving to scale-up the use of the technology at Ulu Pandan. "Our plan is to implement and optimise this technology first at one plant, and subsequently apply it at all other PUB water reclamation plants," says Wah.

Researchers and affiliations

R.J. Xie,* Y.A. Ghani, Y.J. Xing, P.P. Gao, K.E. Ooi and S.W Ng
PUB Singapore

Contacts

xie_rongjing@pub.gov.sg

Fig. 1: The ultrasonic reactor for breaking down sludge prior to microbial processing

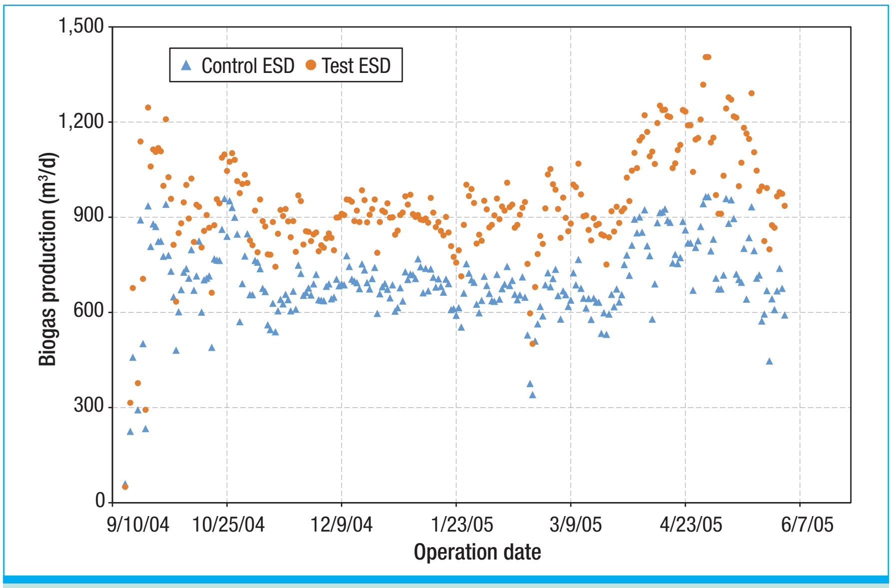


Fig. 2: Biogas output from the ultrasonic disintegration system (orange) is 40% higher than that for the conventional system (blue), and has added benefit of reduced sludge volume

Water Quality and Security

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

Intercepting pathogens in transit

A tailor-made fluorescent readout enables fast, specific detection of bacteria and other pathogens in water

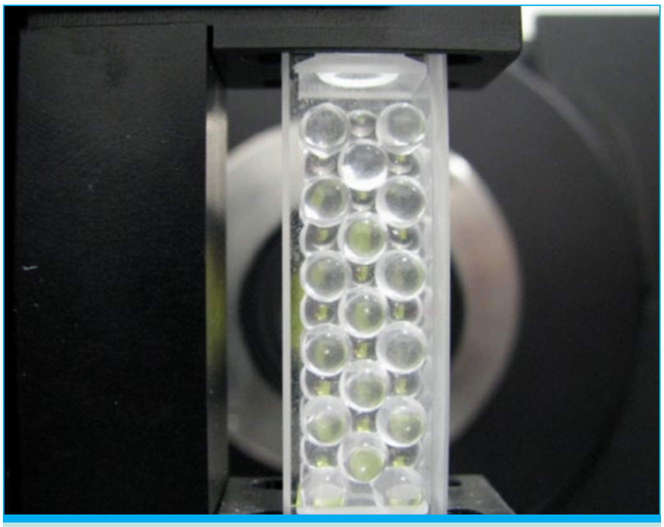


Fig. 1: A cartridge full of tiny glass beads coated with antibodies traps target bacteria in a water sample

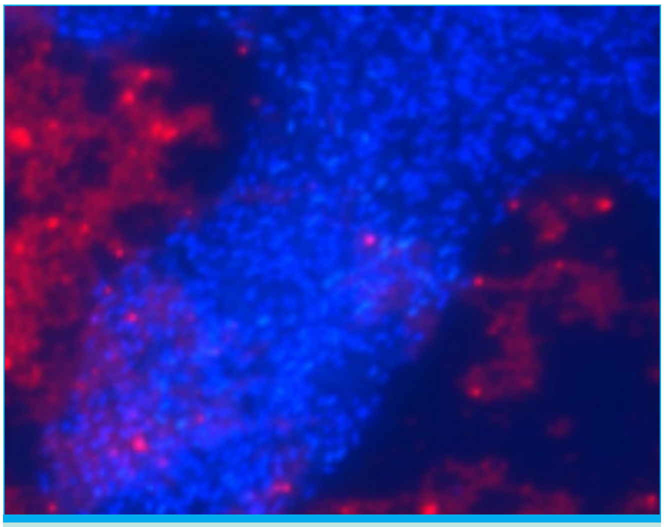


Fig. 2: The presence of *Escherichia coli* bacteria in a water sample is revealed by a red fluorescent signal

Bacterial contamination of public water supplies is always a concern, and efficient and accurate monitoring can turn the risk of it becoming a threat to public health into a minor inconvenience. Unfortunately, most current methods are time consuming, limiting the speed with which authorities can address the presence of pathogens.

"The current standard of detection uses culture-based methods, which typically take 18 to 24 hours," says Karina Gin of the National University of Singapore. Newer methods based on cell and molecular biology techniques have accelerated this process, although these methods are limited by the need to work with small volumes of water samples from the source.

Gin's team recently implemented a promising prototype bacterial detection system, developed in collaboration with scientists from PUB Singapore, which overcomes many of these limitations. "We wanted to devise a way to incorporate a higher volumetric flow into our analysis without compromising the detection capabilities," she says. To achieve this, they paired a technology for the rapid capture of bacteria with a highly sensitive optical detection platform.

The core of the system is a cartridge packed with glass beads (Fig. 1) coated with antibodies chosen for their selective binding to a particular pathogen. Each antibody is also tagged with a fluorescent molecule that only lights up when a target cell binds to the bead. As water flows through the cartridge, bacteria get trapped and their presence is revealed by illumination with a laser. The resulting signal is captured by a highly light-sensitive charge-coupled device camera.

After optimising the system to ensure that the signals obtained from bacterial capture could be confidently distinguished from background noise, Gin and her colleagues accurately detected *Escherichia coli* bacteria in water samples (Fig. 2). Because this strategy is capture-based, it could eventually be suitable for near-real-time monitoring of water quality. "The system could potentially take an offshoot of the flow, have it passed through the cartridge and then analysed optically every few minutes," explains Gin.

Future cartridges could also be optimised for detection of many pathogens simultaneously, by using antibodies labelled with different quantum dots: tiny semiconductor crystals that fluoresce brightly at a specific colour. For now, however, this platform is purely proof-of-concept, and further development is needed before it can be considered for integration into municipal water systems. "Based on the initial results from this project", says Gin, "we are refining the design and will likely pursue future implementation in aquatic environment when ready."

Researchers and affiliations

K. Gin*
National University of Singapore

C.H.Woo and P.P. Gao
PUB Singapore

Contacts

ceeginyh@nus.edu.sg

Boosting surveillance of waterborne pathogens

A tiny chip enables accurate monitoring of the bacterial content of a water sample

Fig. 1: Researchers collecting samples from a pipeline at Yishun in Singapore

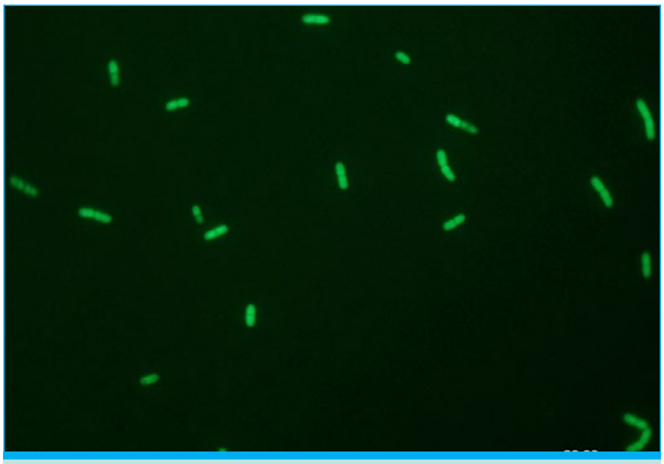


Fig. 2: *Bacillus cereus*, one of the bacteria species identified in the water system

Keeping the water supply clear of pathogens is difficult to achieve, and Singapore faces additional challenges with its tropical climate. "The average temperature is generally above 27 °C, which tends to promote the growth of certain bacteria along the inner surface of the pipeline system," explains Jianzhong He of the National University of Singapore. "Additionally, the biofilms formed in water distribution systems are more resistant to disinfectants, and are capable of harbouring pathogenic microorganisms."

The drinking-water distribution system is one of the most vital infrastructures in Singapore. Existing methods for pathogen detection, however, are inadequate for assessing the impact on water quality throughout the network. To better understand the microbial census in Singapore's water distribution system, He's group partnered with colleagues at PUB Singapore to test a high-speed screening technology known as PhyloChip, which was developed at the Lawrence Berkeley National Laboratory in the US.

The chip contains an array of DNA probes, each of which can specifically bind and detect a target RNA sequence that is unique to a particular bacterial species or strain. This platform enabled the researchers to screen a single water sample containing biofilm from a pipeline for over 30,000 different types of microbe within 24 hours. To assess the microbial population of different pipeline systems, they analysed samples taken from various locations in the Singapore water system where the pipeline age ranged from 14 to 60 years (Fig. 1).

Clear patterns of bacterial accumulation emerged from these data, including more populations of *Alphaproteobacteria* at older sites, although the species identified are relatively harmless to humans. "The disease-causing pathogen *Rickettsia* has not been found in our samples yet," says He. "We found the presence of some medically significant non-*Alphaproteobacteria* strains, such as *Bacillus subtilis* that is associated with food spoilage." They also found *Bacillus cereus* (Fig. 2), which causes food-borne illness.

He believes that this PhyloChip could greatly boost the efficiency of water quality monitoring and make it easier for water utilities and managers to troubleshoot causes of contamination. The system can be used to differentiate between the effects of materials and the age of pipelines or other water-related parameters. "It could also function as a diagnostic tool to check water quality when an operational failure occurs." Moving forward, He's team plans to collect more samples from different locations in Singapore's municipal water system and pair PhyloChip with other analytical methods to selectively track shifts in populations of high-risk microbes in real time.

Researchers and affiliations

J.Z. He*
National University of Singapore

D. Cheng, S. Zhao, C. Ding, R.J. Xie, P.P. Gao and S. Teng
PUB Singapore

C.M. Pang
Ministry of the Environment and Water Resources, Singapore

Contacts

ceehj@nus.edu.sg

Delivering better-tasting tap water

Singapore's tap water is set to improve following the identification and elimination of organic compounds that can affect its taste and smell

Istockphoto/Dmitry Mordvintsev

Unpleasant flavours and aromas that may be present in tap water can be identified and eliminated with treatment

Unpleasant flavours and odours can create a poor impression of water quality—even when it is completely safe to drink. By identifying the organic compounds responsible for these flavours and odours, Lifeng Zhang and colleagues at PUB Singapore, along with a team at the University of California at Berkeley in the US led by David Sedlak, have determined how to eliminate them. The process is based on existing water treatment techniques, and so should be relatively easy to implement.

To identify the compounds responsible for the unpleasant flavours, the team first carried out a flavour profile analysis. A panel of expert tasters sampled the water, and then used an odour wheel to identify compounds souring the water. The amount of each compound in the water was then quantified using an olfactometry gas chromatograph/mass spectrometer. This device separates the compounds in the sample, and allows the user to smell each compound in turn and so detect any 'off-flavour' compounds present (Fig. 1).

Fig. 1: Using the olfactometry gas chromatograph/mass spectrometer in the PUB laboratory

The team could then investigate how each odorous compound first entered the water supply. Some compounds are present in the source water and are not completely removed by conventional water treatment processes, explains Zhang. For example, the compound known as geosmin, which has the aroma of wet earth, is produced by algae in reservoirs.

Some odorous compounds, however, are developed during the wastewater treatment process itself, Zhang adds. To find out how wastewater treatment changes profile of off-flavour compounds in the water, the team developed a bench-scale water treatment process in their laboratory. Their experimental setup simulates the process of treating wastewater using activated sludge.

The team focused on the formation of a family of compounds called haloanisoles, which can give water a musty, mouldy flavour. Using chemically labelled precursors, the team was able to show that 2,4,6-trichloroanisole and 2,4,6-tribromoanisole are formed during activated sludge treatment.

Zhang and his colleagues showed that regardless of the source, most of the unpleasant flavour compounds in water can be eliminated using treatment techniques known to break down organic compounds. "We found that advanced water treatment such as ultraviolet and hydrogen peroxide, or ozone and biological activated carbon, can efficiently remove most of the off-flavour compounds," says Zhang.

Researchers and affiliations

L. Zhang,* X.Q. Qian, R.K. Hu, J.M. Wu, M.H. Lim and Z.G. Yang
PUB Singapore

D. Sedlak and E. Agus
University of California, Berkeley, USA

Contacts

Zhang_lifeng@pub.gov.sg

Water Treatment

For an island nation like Singapore, the development of innovative technologies to optimise water treatment processes for the production of drinking water from seawater is a key element of any water research programme.

However, desalination is a high energy demand process and the energy cost is the biggest impediment to viable commercial development. Singapore carries out innovative research and development efforts aimed at reducing energy consumption for step-wise desalination and our water scientists are looking at alternatives to reverse osmosis technology with the aim of reducing energy requirements still further. In this we draw inspiration from natural systems such as the human kidney and systems that allow marine plants and fish to survive in high salinity environments.

Halving desalination's energy demand

A low-energy desalination technology developed in Singapore could increase the country's freshwater supplies

Singapore taps into the sea around it to bolster its freshwater supply

As an island nation, Singapore is surrounded by water—yet potable water is in short supply. To turn seawater into freshwater, many countries are increasingly using desalination to top up their supplies of drinking water. Desalination, however, is an energy-hungry process, so PUB Singapore is working with multinational engineering company Siemens to modify the process.

In 2008, Siemens won a grant from Singapore's Environment & Water Industry Programme Office to build a demonstration unit that could desalinate seawater using just 1.5 kWh of power for each cubic metre of water that it produced. That energy demand is less than half that used by the best available seawater desalination technologies today, which typically lies in the 3.4–4.8 kWh/m^3 range, says Tim LeTourneau, director of the project at Siemens.

Fig. 1: Inside the new Siemens desalination unit, showing the green ion-exchange membranes

In their bid to achieve that energy target, engineers at Siemens decided to move away from current seawater desalination technologies, which typically use high-pressure pumps to force water through membranes filled with tiny holes, leaving the salt behind. Instead, they turned to electrochemical desalination, which uses an electric field to draw sodium and chloride ions—the constituents of salt—across ion-exchange membranes and out of the water.

"The water doesn't go through the membranes, so the process can be run at low pressure, and hence with low power consumption," explains LeTourneau. Such systems are already used to desalinate mildly salty brackish water, but until now have never been made efficient enough to treat seawater.

Since December 2010, the Siemens demonstration unit (Fig. 1) has been desalting seawater to produce 50 m^3 of drinking water per day at a PUB facility in Singapore. The unit is successfully producing drinking water from seawater using approximately 50% of the energy required by the most efficient desalination technology available today.

Siemens is currently working on turning the small prototype into a commercial system. While it may be possible to drive energy consumption even lower, says LeTourneau, operating costs have to be balanced against the capital cost of the system. Ongoing research also includes the development of cheaper yet better-performing ion-exchange membranes.

"We're proceeding with the technology-to-product transition right now," says LeTourneau. "We hope to reach the next stage of our R&D by later this year, and we hope to then build some full-scale customer pilots next year." One of those customers will be PUB Singapore.

Researchers and affiliations

T. LeTourneau, R. Knauf* and L.S. Liang
Siemens, Singapore

Contacts

ruediger.knauf@siemens.com

Tapping the city streets

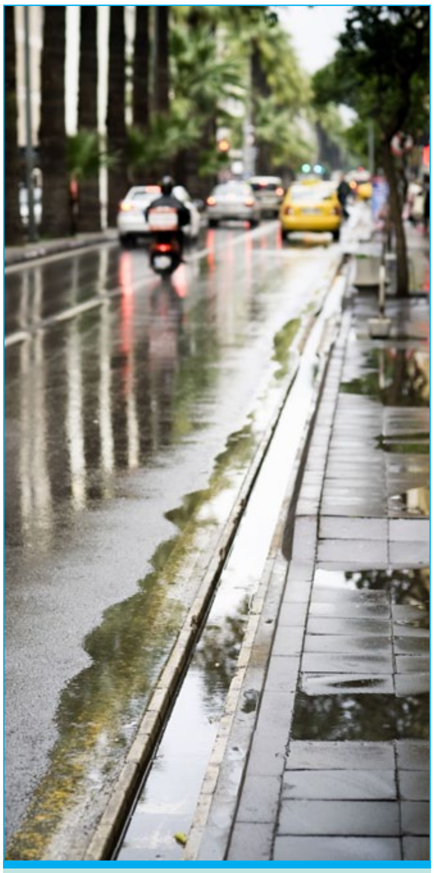
New technique to enhance treatment of urban runoff, a novel water source in Singapore

Singapore is one of the most population-dense countries in the world. Freshwater, however, is scarce, and the country's water agency, PUB Singapore, is always looking for alternative sources of drinking water to supplement its supplies. One of these is urban runoff, which is an abundant source of water in Singapore, especially during periods of heavy rain. Jiangyong Hu at the National University of Singapore, along with collaborators at PUB Singapore, is currently working to test an energy-efficient treatment process to further enhance the treatment of urban runoff.

With Singapore increasingly turning to urbanised water sources such as runoff, increased levels of organic pollutants such as endocrine disruptors and pharmaceutical compounds may be encountered in the future. In order to ensure that a robust treatment system is in place to effectively treat these pollutants, Hu and her collaborators are pilot-testing an emerging technique to improve the treatment efficiency of the waterworks.

The treatment process to be tested is based on a combination of ultraviolet light and hydrogen peroxide. In preliminary tests in the laboratory (Fig 1), the researchers assessed the effectiveness of the process in decontaminating filtered water that they had spiked with pathogens and organic contaminants. The results look promising: the treatment not only kills the pathogens in the water, but also breaks down the organic contaminants via oxidisation. Once treated, the water is passed through a carbon filter, which removes oxidation byproducts and any residual hydrogen peroxide, leaving the water suitable for consumption.

The drawback is that the process is energy-intensive, so the team is also pilot-testing a flexible system that would switch on only when needed. For most of the time, the system would operate in a low power 'disinfection mode', says Hu,



Istockphoto/airportrait

Urban runoff is a potentially significant water resource in Singapore

Fig. 1: This laboratory-scale system tests the removal of organic contaminants that are commonly found in urban runoff

in which only a low dose of ultraviolet would be used to kill any pathogens in the water. However, when elevated levels of organic pollutants are detected upstream, the system would switch to a high-power 'oxidation mode', upping the ultraviolet dose and adding hydrogen peroxide to the water.

The pilot study has just started, Hu explains. Ongoing research includes assessing ways to switch between the different modes of operation, and testing the performance of the downstream carbon filter. Hu and her collaborators are yet to test the system on a real sample of Singapore's urban runoff, but she is confident that it could ultimately be used to treat urban water sources. "This technology should have great potential to deal with that kind of runoff," she says. The pilot test is due to finish by early 2012, after which a decision will be made on its roll-out.

Researchers and affiliations

J.Y. Hu* and X. N. Chu
National University of Singapore

R.J. Xie, T. Pang, E. Quek and Y.J. Xing
PUB Singapore

Contacts

esehujy@nus.edu.sg

Cleaner water from multifunctional membranes

Specially developed anti-fouling filtration membranes for water treatment can neutralise organic and bacterial pollutants

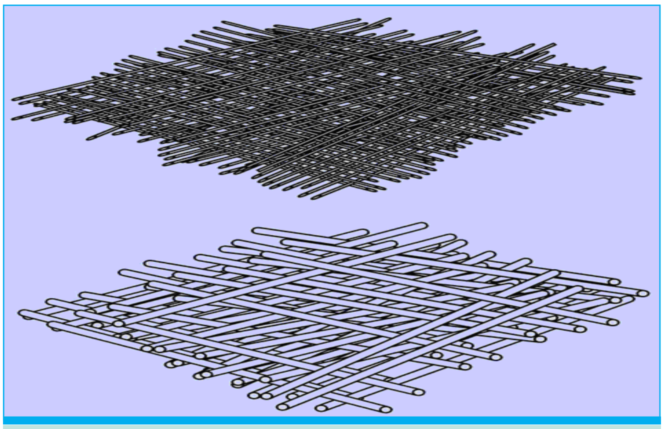


Fig. 1: Schematic profiles of two layers of the nanofibre membranes containing titanium dioxide. The top layer consists of narrow and long nanofibres, while the bottom layer consists of wider and longer fibres.

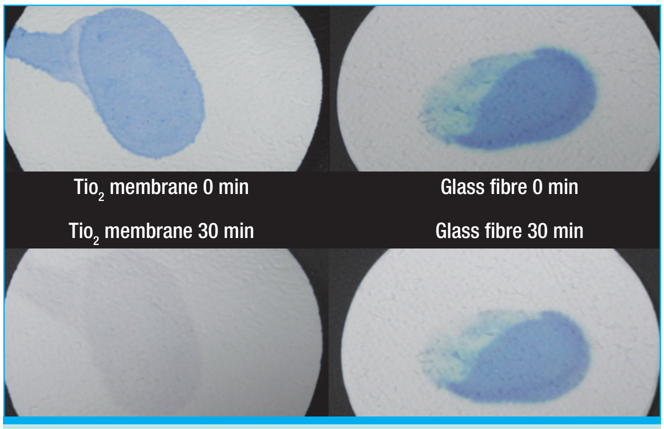


Fig. 2: Under ultraviolet irradiation, an organic substance deposited on the nanofibre membrane (top left) degrades completely within 30 minutes (bottom left) but remains intact on a glass fibre membrane (right)

The accumulation of organic matter in the ultrafiltration systems of water treatment plants can be prevented using membranes made with layers of tiny titanium dioxide (TiO_2) fibres. This new type of membrane is multifunctional—it also degrades organic molecules when exposed to ultraviolet light. The TiO_2-containing nanofibre membranes were developed by a team led by Darren Sun from Nanyang Technological University in Singapore working in collaboration with PUB Singapore.

In conventional membrane-filtration systems, contaminants in water are removed by passing a body of water through filters. The porous filters, depending on pore size, trap polymer- and virus-sized molecules and solid particles. Clogging can eventually result from the accumulation of the retained particles and organic matter, which impedes water flow and can cause a build-up of pressure that can damage the membranes and affect plant performance.

Sun and his colleagues turned to TiO_2 because it is a light-responsive catalyst. In addition to preventing suspended solids from adhering to the filters, the nanofibres decompose large organic contaminants by 'photocatalytic' oxidation, providing the membrane with intrinsic anti-fouling properties.

The researchers fabricated two types of nanofibres that differ in diameter and length, and which self-assemble into distinct porous structures (Fig. 1). After filtering suspensions containing one of each kind of nanofibre, they compressed the layered material using a technique called hot press processing. This process produced a free-standing film consisting of the two types of nanofibre layers interweaved into a tight network, resulting in a mechanically strong and permeable membrane.

An assessment of the size-exclusion properties of the membrane showed that it can filter out polymer-sized pollutants, which is required for ultrafiltration. Flow rates through the TiO_2-containing membrane also outperformed commercially available membranes.

Sun and his colleagues also tested the photocatalytic activity of the membranes for various contaminants (Fig. 2). They observed that ultraviolet light exposure destroyed humic acid deposits on the filters. Moreover, they discovered that the irradiated membranes could inactivate the model microorganism *Escherichia coli*. This inbuilt antibacterial feature eliminates the need for an additional disinfection unit—a boon in the development of water treatment technologies.

Sun notes that the nanofibre membranes will be useful in reducing fouling in many filtration systems. He explains that permeate water can exit a water treatment tank through the TiO_2 nanofibre membrane prior to further filtration. His team is currently studying the energy consumption of this technology before evaluating it for possible implementation in Singapore's water treatment plants.

Researchers and affiliations

D.D. Sun*
Nanyang Technological University

A.N. Pauh
PUB Singapore

Contact

ddsun@ntu.edu.sg

Collaborating institutions and organisations

Local water companies

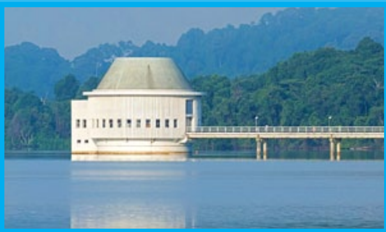
Aromatrix	Singapore
AWA Instruments	Singapore
CPG Corporation	Singapore
Darco Water Technologies	Singapore
DHI Water & Environment	Singapore
Graham Tek	Singapore
Hyflux	Singapore
Keppel Corporation	Singapore
Membrane Instruments and Technology	Singapore
Memstar Technology	Singapore
memsys clearwater	Singapore
Moya Dayen	Singapore
Optiqua Technologies	Singapore
Pan Asian Water Solutions Limited	Singapore
Sembcorp Industries	Singapore
The Glowtec Environmental Group	Singapore
Ultra-Flo	Singapore
United Engineers	Singapore
United Envirotech	Singapore

International research institutions

Awwa Research foundation	USA
Delft University of Technology	Netherlands
Deltares	Netherlands
ETH Zurich	Switzerland
Flinders University	Australia
Massachusetts Institute of Technology	USA
Peking University	China
Sandia National Laboratories	USA
Stanford University	USA
The Commonwealth Scientific and Industrial Research Organisation	Australia
The Global Water Research Coalition	UK
The University of New South Wales	Australia
The University of Oxford	UK
The University of Queensland	Australia
The University of Western Australia	Australia
University of Canterbury	New Zealand
University of Illinois at Urbana-Champaign	USA

International organisations

Asahi Kasei Corporation	Japan
Black & Veatch Corporation	USA
Camp Dresser & McKee Inc.	USA
CH2M HILL	USA
Dow Chemical Company	USA
Endress+Hauser Instruments International AG	Switzerland
General Electric Company	USA
Hitachi	Japan
Huber Technology Inc.	Germany
ITT Water & Wastewater	USA
IWS	UK
Koch Membrane Systems Inc.	USA
Kuraray	Japan
Kurita Water Industries	Japan
Meidensha Corporation	Japan
Mekorot	Isreal
Metawater	Japan
Mitsubishi Rayon	Japan
Nitto Denko Corporation	Japan
Norit NV	Netherlands
Orange County Water District	USA
Pall Corporation	USA
Pulverdryer	USA
PWN Technologies	Netherlands
Queensland Government	Australia
Rand Water	South Africa
Rehru Unlimited Polymer Solutions	Germany
Saline Water Conversion Corporation	Saudi Arabia
Severn Trent Service	USA
Siemens	Germany
SUEZ Environnement	France
Teijin Limited Corporate	Japan
Toray Industries	Japan
Veolia Environnement	France
Vitens	Netherlands
WateReuse Research Foundation	USA



PUB

Water for All: Conserve, Value, Enjoy

FOR FURTHER INFORMATION, SEE:

www.pub.gov.sg