INNOVATION IN WATER SINGAPORE

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PUB

Water for All: Conserve, Value, Enjoy

An R&D publication of PUB, Singapore's national water agency | April 2013 | Volume 4

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, 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.

Launch of new R&D online portal *SINGwater*

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

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

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

PUB, Singapore's national water agency
40 Scotts Road #22-01 Environment Building
Singapore 228231
www.pub.gov.sg

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Message from the Executive Director

Welcome to the fourth issue of *Innovation in Water | Singapore*.

In this issue we continue our exploration of progress in water-related R&D initiatives across Singapore. In the previous issue, we highlighted the important role played by PUB, Singapore's national water agency, in driving innovation in water technologies. In addition, we featured Siemens' Global Water R&D Center's investigation into a more cost-effective desalination solution, and showcased the company's efforts to reduce the energy required for seawater desalination—one of our Four National Taps. Siemens' technology exploits electrodialysis—an electrochemical process that facilitates the transport of ions through an ion exchange membrane—to remove the contamination that renders seawater nonpotable. An overarching theme in this current issue is the effective collaboration between PUB and both local and international institutions in pioneering R&D for new water management techniques. This is demonstrated in our projects such as the Wireless Water Sentinel (WaterWiSe), the focus of this issue's "Feature" article. WaterWiSe is a real-time water quality and distribution monitoring system, where in collaboration with Visenti Pte Ltd—a company which focusses on improving infrastructure management—we have successfully deployed a network of sensors around Singapore that help to improve the operational efficiency of the water supply system.

In the last issue, two new sections—"Facilities Focus" and "People in Water Research"—illustrated the infrastructure and scientific expertise that PUB taps into. We introduced our extensive network of facilities that provide a real-world test bed for commercially transferable water resource management technologies, and Mr Tan Gee Paw, PUB's chairman, discussed the role of leveraging technology for the provision of a sustainable water supply for Singapore. This issue's "Facilities Focus" continues to investigate the key PUB-managed water value chain facilities across Singapore and underscores the many benefits they offer for research and test-bedding. In "People in Water Research", Dr Joan B. Rose—an international authority on microbiology, water quality and public health safety, and chairperson of the PUB External Audit Panel—reflects on her experiences throughout her distinguished career in Singapore's water research community.

Collaboration with industrial and academic partners has always been PUB's core effort in accelerating research progress within the field of water studies. To date, PUB has fostered 388 R&D project partnerships, collectively valued at over S$280 million. In the future, we anticipate that the number of such alliances will grow, increasing the fruits of their labour.

This issue also rounds up the latest R&D highlights from laboratories and companies affiliated with PUB—including advances in water quality management and treatment. I encourage you to appreciate how these significant findings help further our collective mission to ensure an adequate, efficient and sustainable supply of water for Singapore.

Chew Men Leong
Chief Executive, PUB, Singapore's national water agency
Executive Director, Environment & Water Industry Programme Office

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Innovation through collaboration: Singapore as a global hub for water research and development

Spearheading the most advanced initiatives across the entire water value chain, Singapore is fast becoming a global hydrohub for water research and development. By investing in R&D and integrating excellent management practices, Singapore's water management strategies aim to secure a sustainable water supply to meet the growing demand of its population and industries. In collaboration with government agencies, industry partners and academia, PUB, Singapore's national water agency, plays a key role in nurturing the development of a world-class water industry. PUB's R&D activities not only encourage new ideas and technology but also position Singapore as one of the world leaders in water resource research and management strategies.

Throughout history, water has confronted humanity with some of its greatest challenges. Water is a source of life and a natural resource that sustains our environment and supports livelihood—but it is also a source of risk and vulnerability. Singapore, with its limited land area, high level of urbanization and a lack of natural freshwater lakes, faces many obstacles to meet its domestic and industrial water demands. As a densely populated city-state of over 5 million people, Singapore's demand for water comes to almost 380 million gallons of water per day. In just 50 years, this demand is expected to double.

Singapore's unique water resource environment requires innovative water management solutions. Remarkably, some 40 years ago, Singapore identified the need to harvest unconventional water sources to augment supplies provided by natural catchments. To this end, the government established a comprehensive research and development (R&D) programme and adopted new water treatment technologies. NEWater technology—developed in Singapore for the production of high-grade reclaimed water from treated, used water—is one such example. Together with water from local catchments, imported water and desalinated water, Singapore has instituted a robust, diversified and sustainable water supply known as the Four National Taps. By taking an integrative approach to maximize the efficiency of the Four National Taps, strategic initiatives and partnership projects are underway to harness Singapore's research strengths, elevating the city-state as a world leader in the application of recycled water and sustainable water management solutions.

Comprehensive research and development

As the national water agency, PUB takes on the leading role in water R&D in Singapore through the Environment and Water Industry Programme Office (EWI), an inter-agency body that also includes the Economic Development Board (EDB), International Enterprise Singapore (IE Singapore), the enterprise development agency SPRING Singapore, as well as academic partners including the National University of Singapore (NUS), Nanyang Technological University (NTU) and the Agency for Science, Technology and Research (A*STAR). This whole-of-government strategy implemented through the EWI integrates policy and implementation frameworks across the various agencies involved in the development of the water industry.

Through the EWI, PUB works closely with research and academic institutions as well as the private sector. Within PUB itself, a number of departments also conduct in-house research, helping to solve operational issues and improve operational efficiency. In this way, PUB acts as a bridge between research and downstream application, adding value to its collaborative partnerships. Moving forward, PUB and the EWI are firmly committed to working closely with leading academic institutions around the globe to encourage new ideas and innovations.

At the same time, the Environment and Water Research Programme (EWRP) aims to accelerate the process of transforming new ideas and technology into innovative applications that can eventually be commercialized. The EWI also focusses on grooming talented individuals to meet the rapidly growing needs of industry and research institutions. In addition to training research personnel and engineers, PUB supports several graduate scholarship programmes and is active in developing local knowledge capacity by inviting internationally renowned experts to collaborate with researchers in Singapore. These initiatives have since elevated the international profile of Singapore as a global hydrohub, attracting large-scale investments and high-calibre researchers to the nation's shores.

Coming together for water innovations

PUB's commitment to fostering research partnerships with local and international research organizations, water utilities and technology solutions providers has resulted in a number of major collaborative R&D projects. Advancements in polymeric membrane materials, which have greatly benefited seawater desalination and water reuse today, are unparalleled examples. With considerable depth of expertise in the water industry and willingness to share its facilities for research, PUB welcomes collaboration with both industry partners and individuals on research that supports the provision of a high-quality, sustainable water supply for Singapore.

A big drawcard for water R&D in Singapore is the availability of PUB's extensive network of waterworks, including water reclamation plants, NEWater plants, reservoirs and stormwater canals, for testing new technologies. The opportunity to conduct on-site testing under actual conditions is crucial for the development of technologies that can be commercialized. To work with the private sector, PUB has about 150 officers in 6 technology groups—Intelligent Watershed Management, Membrane Technology, Network Management, Used Water Treatment, Water Treatment, and Water Quality and Security—to help with the transition from fundamental research to test-bedding and pilot demonstration-scale studies. The officers also conduct studies to improve operational issues to facilitate implementation of new technologies in PUB's daily operations.

PUB's collaborative strategy allows the costs of R&D to be shared, while reducing associated risks. The funding schemes available include the EWI's Incentive for Research and Innovation Scheme and TechPioneer Scheme, and the EDB's Innovation Development Scheme. The long-standing success of PUB's collaborative R&D demonstrates that partnerships often result in the transfer of complementary expertise, creating a win-win situation for all parties.

The World Health Organization (WHO) has also designated PUB's Water Quality Office as a WHO collaborating centre for safe drinking-water management and integrated urban water management. This recognition is a testament to Singapore's position as a global hydrohub and boosts Singapore's rise to the forefront of water research.

Water solutions for a thriving future

According to the United Nations Educational, Scientific and Cultural Organization (UNESCO), 27% of the current urban population in the developing world does not have in-house piped water, hence prompting an urgent need for robust systems in potable water supply and distribution. Going forward, Singapore continues to drive technological innovations to overcome water supply challenges. Working with local and global collaborators, the realization of this vision is perhaps much closer than we think.

Keeping a close eye on the flow

Since independence in 1965, Singapore has identified the need to provide a sustainable supply of clean water for its people as a critical goal. The scarcity of natural water resources and the limited land area posed major challenges but Singapore was not deterred. In a truly remarkable reversal, the young nation has transformed its vulnerability into a strength by adopting an integrated approach to water management, implementing sound water policies and investing in water technologies.

In many developed cities around the world, potable water distribution infrastructure is rapidly ageing and deteriorating, leading to compromised water quality and increased frequency of delivery failure. To prevent such problems, water distribution systems need to be adequately managed and maintained. In Singapore, where natural water resources and space are both limited, this need has motivated the development of robust systems for securing a sustainable supply of clean drinking water to its population of over five million people.

Singapore's WaterWiSe Project

For a water utility to cater to the needs of consumers efficiently, system operations such as managing leakage control and minimizing the impact of repairs and maintenance have to be closely monitored. This necessitates an accurate assessment of the state of the water distribution system. To realize this, Singapore has successfully installed an expansive sensor-network-based infrastructure for continuous and accurate monitoring of the water distribution system. Since 2008, a major research project known as the Water Wireless Sentinel at Singapore (WaterWiSe) has been established. Supported by the Singapore National Research Foundation (NRF), this project is an international multi-party collaboration involving PUB, Singapore's national water agency, Massachusetts Institute of Technology (MIT), the Center for Environmental Sensing and Modeling (CENSAM) of the Singapore–MIT Alliance for Research and Technology (SMART), the Intelligent Systems Centre (IntelliSys) and the School of Computer Engineering (SCE) at Nanyang Technological University (NTU), as well as Visenti Pte Ltd—a spin-off company established in 2011 from WaterWiSe.

The WaterWiSe project consists of three phases. In Phase 1, a basic system with a selected number of sensor nodes was installed to demonstrate the viability of long-term monitoring and data collection. Phase 2 saw the expansion to 26 wireless network sensor nodes, enabling online monitoring of hydraulics and water quality within the distribution system in the Fort Canning–Pearl's Hill (FCPH) zone of central Singapore. The third phase focussed on developing and evaluating a new generation of multiprobes that have enhanced sensing functionality.

Comprehensive sensing capabilities

In the initial phases of the WaterWiSe project, the sensor nodes measured the pressure, acoustics, pH and the oxidation–reduction potential of water in the distribution system. By incorporating additional sensors to measure flow, electrical conductivity and temperature, the WaterWiSe team developed a new generation (v3) of multiprobe nodes (Figure 1). Novel instruments were added and the sensor node was completely redesigned to include a low-power sleep mode that reduces power consumption. In the FCPH zone, nodes are installed above ground and are powered by batteries that are recharged by solar panels and adjacent street lights (Figure 2).

Real-time information anytime, anywhere

Many water utilities employ limited online monitoring and analysis within their systems; instead, they rely heavily on feedback from a sub-system of a few thousand consumers at inlets and outlets of the distribution system. At that level, it is sometimes difficult to pinpoint problem areas with respect to leakages, water age and water quality. To realize constant real-time monitoring of infrastructure status, the WaterWiSe team developed a central, online server that can be accessed from any web browser to visualize live or archival data. In addition, the event tracking capability of the server performs a series of statistical tests to identify outlier events such as pipe bursts or leaks, water quality anomalies or malfunctioning nodes (Figure 3). When such events occur, notifications will be automatically sent to subscribers, including PUB engineers, expediting appropriate responses.

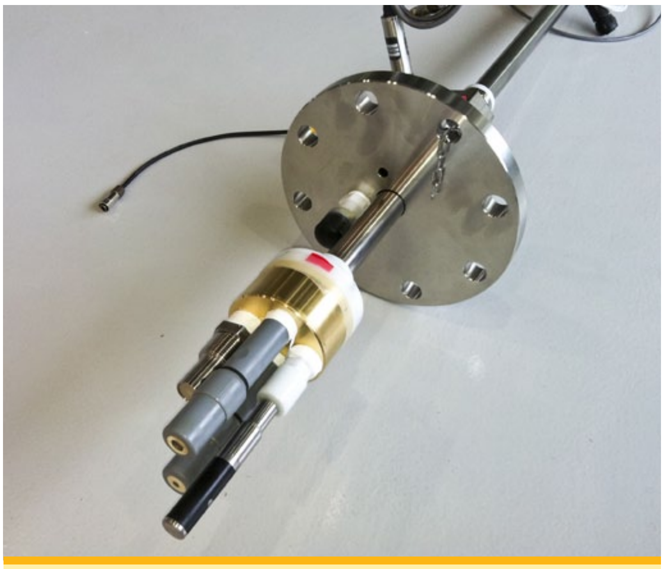


Fig. 1: Additional sensors were incorporated in the new-generation v3 multiprobe nodes

Fig. 2: The new nodes are powered by batteries that are recharged by solar panels and adjacent street lights

To develop a model for predicting water usage, a third service was incorporated in the central server. This function was based on the online hydraulic model developed in previous phases of the WaterWiSe project, which identifies virtual demand zones in homogenized clusters of consumers. A predictor–corrector algorithm was employed to forecast future water demand in individual zones served by different reservoirs. The incorporation of a well-calibrated hydraulic model in the FCPH network has made it possible to study other physical properties of the distribution system, including water age and source mixing (Figure 4).

Refinement through simulation

One of the key developments during Phase 3 of the WaterWiSe project has been the development of a hydraulic simulation tool. It allows the team to evaluate the effects of operational and field events, such as valve closure or pipe isolation, on the surrounding pipe network. Using this simulation tool, low or reverse flow in pipe links can be identified and diagnosed, ensuring optimum water quality. Since its implementation, the hydraulic simulator has been closely monitored and reviewed by PUB engineers to facilitate continuous refinement. In the near future, field trials will be performed with tablet computers to realize full mobility and convenience.

Novel methods for pinpointing anomalies

Within a water distribution system, sudden pipe bursts can occur in high-pressure water transmission mains and distribution pipelines. The ability to detect and localize pipe bursts and leaks quickly is extremely important, as outage time incurred by repair works can be costly. In preparation for such incidents, the WaterWiSe team adopted new algorithms for predicting and interpreting pressure transients associated with simulated pipe bursts. The new methods were tested in the City Hall area, a bustling downtown precinct in Singapore with a high volume of retail and commercial activities. A test programme involving a simulated pipe burst was conducted with six sensor nodes located at distances up to 1 kilometre from the source. In these tests, two detection methods were used—statistical analysis to identify outlier pressure events, and multiscale wavelet decomposition for accurate and consistent interpretation of wavefront arrival times. Data from the intensive tests culminated in a refined method capable of locating the source of a burst with an average accuracy of 20 metres. To date, the WaterWiSe team has identified and reported several major hydraulic events to PUB, including one that occurred in Marina South, a newly developed leisure area.

Clean, sustainable water for everyone

With the successful completion of all three phases of the WaterWiSe project, the team is committed to ensuring sustainable and efficient supply of potable water to millions of Singaporeans on a daily basis, as well as sharing their knowledge with the rest of the world. The team is ready for the new task of promoting the WaterWiSe project to world-leading status. Additional pipe burst experiments and hydraulic modelling will be conducted, together with extending the capabilities of the hydraulic simulator to optimize strategies for managing anomalies. In collaboration with Sandia National Laboratories, a prominent energy research body in the United States, a system known as CANARY will be implemented for ongoing calibration and tuning of the detection algorithms used in the v3 nodes. Finally, in preparation for the next large-scale initiative, new research into strategies for optimizing pump operation—spearheaded by Visenti Pte Ltd—will commence with the deployment of sensor nodes in the Queenstown High-Pressure Zone of southwestern Singapore, to allow the real-time monitoring of water quality parameters and reporting of outlier events.

Fig. 3: Insertion probes detect anomalies at various points throughout the water distribution system

Fig. 4: The incorporation of a well-calibrated hydraulic model allows study of physical properties of the distribution system

PEOPLE IN WATER RESEARCH

Joan B. Rose

Chairperson of the PUB External Audit Panel

Joan B. Rose began her education in the field of microbiology at the University of Arizona, US, graduating in 1976 with a Bachelor of Science. She obtained a Master of Science from the University of Wyoming, US, in 1980, which was followed by her return to the University of Arizona to conduct her doctoral studies, leading to the award of PhD in 1985. Since 2003 she has held the Homer Nowlin Chair in Water Research at Michigan State University, US. In 2001 Rose became the first female recipient of the US National Water Research Institute's Clarke Prize for her contribution to water science and technology research. She was presented with the inaugural Hei-jin Woo Award for Achievements of Women in the Water Profession by the International Water Association in 2008. In 2009 she received a Public Service Medal from the Singapore Ministry of Environment and Water Resources. Rose was elected a Fellow of the American Association for the Advancement of Science (2010) and also inducted into the US National Academy of Engineering (2011).

Achieving water security for Singapore

In 2004 as part of a team made up of Singaporean scientists, engineers and public health experts, I found myself walking into a room full of journalists, policy makers and interested members of the public. All were eager to know more about the results of a five-year, ground-breaking research project into a new approach to obtain water security for Singapore.

The start of an adventure

My association with the project began in 1999 when I was asked to serve the Singaporean Ministry of the Environment and Water Resources, and PUB, Singapore's national water agency, in an advisory capacity. I was excited to be travelling to the other side of the world to work in an exotic city-state with a history enriched by economic development, freedom and diversity. The team's research facilities in the east of Singapore consisted of a trailer positioned at the now-decommissioned Bedok Water Reclamation Plant. Here we examined the design and assisted in the implementation of a pilot plant for the study of the advanced treatment of used water, our aim being the production of a high-quality water for use in industry, and additionally to help fulfil the water demands of the population.

Water sorcery

My own research expertise encompasses the areas of microbiology, water quality and public health. However, my previous studies of reclaimed water during my time in the US were focussed on that used for the irrigation of crops or lawns. In contrast, the Singaporean project evaluated water quality using a high-technology approach that involved microfiltration followed by reverse osmosis and ultraviolet light disinfection. The water that entered and exited the plant at each treatment step was monitored for various chemicals and microorganisms. Using the evidence obtained we were able to consistently verify the production of a high-grade reclaimed water—now known as 'NEWater'—that was pure enough for anyone to drink.

Despite the annual 2,400 millimetres of rain that Singapore receives, in the past, much of the water that had supplied the country came from Malaysia. The legacy of water recycling projects, such as NEWater, is therefore clear: they have greatly assisted in achieving water security for Singapore, and provide the country with the resilience required to withstand economic and climate change.

Reflections on water research from Singapore

Since the research project's conclusion in 2004, I have been privileged to continue to serve PUB as chairperson of the External Audit Panel, examining the government's ever-expanding perspective on water sustainability and the Four National Taps. Experiences gained while working in Singapore have framed my world view of water, and helped me to better understand the actions required to serve the cause of providing clean water around the globe. I have gained a thorough understanding of the philosophy that underlies PUB's water-related research, and am amazed at the progress they have made. I have also come to realize it is of great importance that the research community, together with PUB and its industrial partners, place diligent testing of water quality as one of their key priorities. As a microbiologist, I believe that the provision of safe drinking water is the basic building block of a healthy and successful society.

Sharing knowledge to advance water research

I expect that future advances in water technology will be catalysed by new approaches pioneered through research partnerships with the private sector combined with an open attitude to the sharing of knowledge. Singapore has succeeded in creating a global hydrohub that is now being emulated around the world. It is a hub with which global companies wish to set up partnerships, where students and professionals alike may continue their water science and technology-based education, and that offers a platform for the comprehensive discussion of water-related issues. Singapore is consequently in the commendable position of being able to assist the international community with the knowledge it has acquired through its investment in water research. Personally, I feel extremely fortunate to have played a small part in helping Singapore shape the way the world understands water.

A test bed of water innovation

In Singapore, a young island nation not naturally endowed with an abundance of land or freshwater, the development of new technologies to ensure an efficient and sustainable supply of water at an affordable cost is of paramount importance. Innovations such as NEWater—a high-grade reclaimed water produced from treated used water, and the jewel of our water supply strategy—have been instrumental in diversifying and expanding the city-state's water sources.

Translating new ideas for water management into practical solutions requires trials to be conducted under the actual operating conditions of real infrastructure. While the traditionally cautious approach of technology developers ensures the absolute safety of water supply at all times, it can, however, stifle potential innovations in water management. This catch-22 situation has hindered the conception and implementation of many promising water technologies around the world.

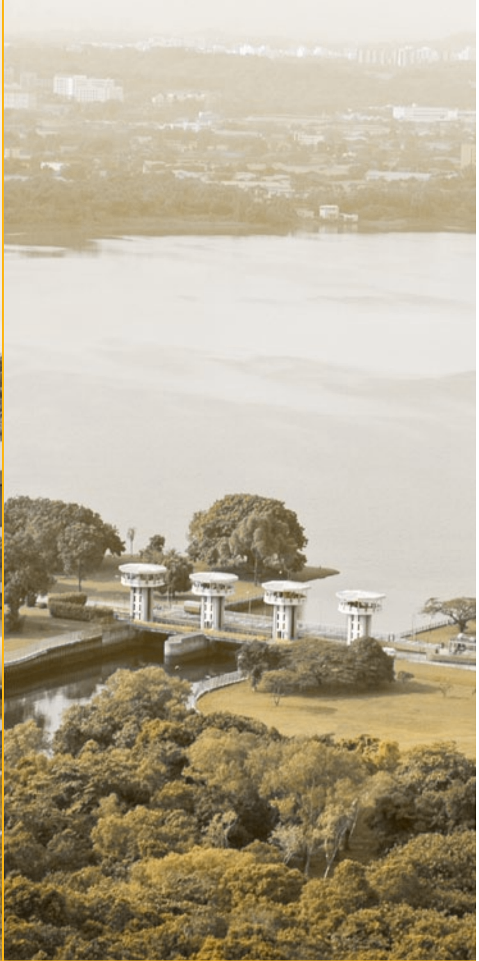
Through the Environment and Water Industry Programme Office (EWI), PUB, Singapore's national water agency, has established a framework of facilities—including waterworks, water reclamation plants, NEWater plants, reservoirs and storm canals—as test-bedding sites for technology developers in both public and private sectors. Over the past 2 years, more than 30 R&D projects have been approved for test-bedding at these facilities. PUB's efforts encourage the early adoption of novel water technologies and provide a valuable opportunity for technology developers to establish a successful track record of trials performed under real operating conditions. This in turn allows PUB to fast-track the introduction of novel, proven technologies in order to uphold its mission of ensuring an efficient, adequate and sustainable water supply. At the same time, this initiative firmly positions Singapore as a global test bed for water resource research and development.

Where new technologies are proven

Singapore's catchments and waterways are also available as sites for research and test-bedding. The Marina Catchment is Singapore's largest and most urbanized catchment with an area of approximately one-sixth the size of Singapore. The Marina Barrage built across the mouth of the Marina Channel to form the Marina Reservoir—Singapore's fifteenth reservoir—was used as a test-bedding site for memsys Clearwater Pte Ltd. In collaboration with Nanyang Technological University (NTU), a solar loop was integrated with the memsys membrane distillation (MD) system allowing solar desalination of seawater. "The exposure we received from the project was very helpful for a relatively young company like memsys. Even today, we get emails and calls from interested customers and partners referencing this project and wanting to discuss the memsys MD technology for solar desalination and other water treatment applications in the industry," remarks Niranjan Sarda, international sales director of memsys Clearwater Pte Ltd.

Allowing continual improvement

For projects related to potable water, testing can be conducted at PUB's waterworks. Choa Chu Kang Waterworks (CCKWW), one of the largest waterworks in Singapore, offers its facilities



Developing cutting-edge water technologies with the advantage of PUB facilities

to Hyflux Ltd to test-bed their proprietary ultra-filtration membranes. Through data collected from the past three years, Hyflux Ltd has gained a better understanding of the performance of each membrane. Esther Lee, a staff member from Hyflux Ltd, explains: "By analysing the data collected at CCKWW, we have identified a number of areas for improvement and have subsequently made modifications to enhance the design and efficiency of the membrane and pilot plant. All in all, the test-bedding project has been an invaluable learning experience for us."

Offering superlative support and technology to the world

Projects involving used water can be conducted at PUB's water reclamation plants (WRPs). A number of such projects are currently being conducted at the Jurong Water Reclamation Plant (JWRP), including the second test-bedding of Glowtec Bio Pte Ltd's Aerobic Granule Membrane Bioreactor Wastewater Treatment System. "PUB's JWRP provided us with a unique environment for trialling our system across various waste water sources, such as industrial used water and municipal sewerage," explains Monica Yeo, regional office manager of Glowtec Bio Pte Ltd. Since the commencement of their prototyping operations, Glowtec Bio Pte Ltd has successfully accumulated sufficient data on the performance of their systems over various used water streams to optimize operational parameters in a large-scale environment. "Working with PUB over the last few years has allowed our research team to gain crucial practical operational experiences," adds Yeo.

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1. memsys Clearwater Pte Ltd test-bedded a membrane distillation system with an integrated solar loop at the Marina Reservoir, for use in seawater desalination
2. Glowtec Bio Pte Ltd found the perfect environment to test-bed its Aerobic Granule Membrane Bioreactor Wastewater Treatment System at Jurong Water Reclamation Plant
3. The ceramic membrane demonstration plant at Choa Chu Kang Waterworks was used by PWN Technologies to evaluate the performance of its CeraMac system

For some technology developers, further testing and validation of their innovations is required to step up the scale of the technology. One company that has benefited from this is Baleen Filters Pty Ltd. The Australian company, which supplies filters for separation of suspended matters from industrial, mining and municipal used water, has carried out testing of its products at three of PUB's WRPs. "The positive results of our first test-bedding at Kranji led to the two subsequent projects at Changi and Ulu Pandan. The site services, electricity and water required were reliable and efficiently supplied," says Robert Crewdson, Southeast Asia representative for Baleen Filters.

The commonly used aerobic biological used water treatment processes create several environmental problems, including high energy consumption, generation of large amounts of sludge and carbon dioxide emissions. In search of a novel concept to tackle such issues, Siemens tested their Waste to Energy Process initiative at Ulu Pandan WRP with the aim of converting inherent energy in domestic used water to usable energy. This energy source could either be used to power up the used water treatment plant or be returned to the power grid. "This initial proof of concept pilot ran for about three years, allowing us to gather ample invaluable data," shares Bobby Ding, research scientist at Siemens. "The data was used for scaling up to a higher flow rate, with the overall concept proving to be more attractive from an economic point of view. Subsequently, by cutting life cycle costs, we could offer more competitive benefits to end users."

Scaling new heights

Further to test-bedding of pilot concepts, the technologies at PUB facilities can be applied to a larger demonstration scale. The ceramic membrane demonstration plant, currently being tested by Dutch advanced water technology company PWN Technologies (PWNT) at CCKWW, is one such example. The polymeric membrane plant at CCKWW provided the necessary infrastructure for the company to evaluate the performance of its CeraMac system based on water quality and data efficiency. "CCKWW's ozone system enabled us to compare and evaluate the combination of ozone and the CeraMac system, leading to the development of a highly cost-effective solution for cleaning ceramic membranes," relates Jonathan Clement, director of technology application at PWNT.

Singapore is always on the lookout for innovative water solutions and is committed to the ongoing mission of providing the most conducive environment for technology developers around the world to test new ideas via PUB's extensive network of facilities. The test-bedding projects mentioned above are just a few examples of the positive experiences shared by private companies using PUB's facilities. For more information on test-bedding opportunities at PUB's cutting-edge sites, please visit **pubwateresearch.com.sg**.

4. Hyflux Ltd's test-bedding at Choa Chu Kang Waterworks allows the company to improve membrane design and efficiency
5. Baleen Filters Pty Ltd tests the performance of its filters at one of PUB's water reclamation plants
6. Test-bedding has allowed Siemens to further validate the technology of converting inherent energy in domestic wastewater to usable energy

Intelligent Watershed Management

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

Stormwater under the spotlight

Characterizing heavy metals in urban storm runoff will further improve Singapore's water catchment management

Fig. 1: Water collected from urban runoff following a storm can carry a high contaminant load

Fig. 2: Automated stormwater sampling devices installed at sites across Singapore are measuring the levels of heavy metal contaminants

In a highly urbanized country such as Singapore, urban runoff can provide a significant proportion of the population's freshwater supplies. Such water supplies, however, can contain higher pollutant loads than water sourced from pristine, undeveloped environments. Lloyd Chua at Nanyang Technological University and his collaborators at PUB Singapore are currently assessing the potential risks posed by contaminants in urban runoff across Singapore (Fig. 1).

The researchers are focussing on heavy metal pollutants, which can be problematic because they do not biodegrade. Once released into the environment, during industrial activity for example, heavy metals can accumulate in the sediments of nearby rivers and streams. Long after deposition, an event such as a storm can trigger the release of these metals back into the water column.

In their assessment, Chua and his colleagues first examined heavy metal accumulation in the sediment beds of Singapore's urban water sources. Using a technique called atomic emission spectroscopy, they analysed sediment samples collected from drainage sites across the country to check the levels of four key heavy metals: cadmium, copper, lead and zinc.

Analysing their results using the US Environmental Protection Agency's sediment quality guidelines, the researchers found that 24% of sampled sites contained elevated lead levels. Cadmium, in contrast, was more broadly distributed, occurring in significant quantities at 68% of sites sampled. "In general, higher concentrations were found at sites with significant industrial activity," Chua says.

Alongside the sediment sampling work, the team is also assessing the release of heavy metals from urban areas during storms. They installed automated stormwater sampling devices at one residential and four industrial sites across the country, collecting samples during 30 storm events (Fig. 2). Chua and colleagues analysed each sample for heavy metals using mass spectrometry. As expected, they found higher quantities of the metals in samples collected at the industrial sites than the residential area.

Chua and his team are now using fine sieves to fractionate the particles present in each stormwater sample. Some previous studies have indicated that, for particular metals, finer particles dominate the pollutant load in stormwater. "Fractionating our samples will allow us to determine the dominant particle size range of a pollutant, which will enable us to understand the settling behaviour of these pollutants," Chua explains. After completing the sample collection and analysis phase of their project, Chua and his colleagues will be able to map heavy metal particle size distribution in Singapore's stormwater.

Researchers and affiliations

L. H. C. Chua
Nanyang Technological University, Singapore

H. S. Eikaas, K. M. Tan
PUB Singapore

Contact

Lloyd H. C. Chua; CHCChua@ntu.edu.sg

Clouds with benefits

Sensor networks and cloud computing allow real-time monitoring of the water quality of Singapore's reservoirs

Fig. 1: A system of sensors that provide researchers with a continuous stream of water quality data is being trialled in Marina Reservoir (pictured)

Fig. 2: From the large amounts of real-time water quality data sent to the cloud, researchers in Singapore can quickly analyse water quality using computer aquatic ecosystem models such as ELCOM-CAEDYM

In Singapore's tropical climate, measuring and analysing water quality quickly and accurately is important. Extensive data collection and high computing power are required to run prediction models so that appropriate actions can be taken as soon as possible to guard against the effects of any deterioration in water quality.

To expedite predictions, Bingsheng He and his colleagues at the Nanyang Technological University, Singapore, together with scientists at PUB Singapore and Hong Kong University of Science and Technology, are trialling a novel method of modelling water quality that uses wireless sensor networks and the processing power of cloud computing.

"We are working on a real-time water quality monitoring system that permits repeated simulations on a large scale," explains He. "Wireless sensor networks are currently in place at two reservoirs, Kranji and Marina (Fig. 1), to provide us with continuous data."

The sensors collect a large volume of data on different aspects of water quality and wirelessly transmit the information to a main hub. The data packages are then sent to the cloud—many computers accessed remotely via the Internet—where multiple simulations can be run (Fig. 2). In their new system, the model can run at speeds 40 times greater than usual.

The team is using an integrated three-dimensional (3D) hydrodynamic-ecological model called ELCOM-CAEDYM, which was developed by the University of Western Australia, to run daily 3D simulations of the reservoirs. This model allows researchers to predict many factors that affect water quality, such as algae levels in water under certain climatic and environmental conditions. The researchers are adapting the model parameters so that they are appropriate for Singapore's environment.

"Compared to deep temperate lakes, the water quality variables of shallow tropical reservoirs in Singapore vary on a shorter, daily timescale," explains He. "Also, the nutrients and phytoplankton characteristics are different here, requiring model parameters to be optimized."

Real-time monitoring means that changes in water quality due to sudden events, such as storms, can trigger an alarm in the system. "In a tropical storm event, the ELCOM-CAEDYM model will forecast changes to critical water quality variables for the near future," he notes. "Or if algae concentrations exceed a set limit, an alarm [will be] triggered and local authorities such as PUB will be notified to take appropriate action. This allows fast, effective responses that will avert potential public health risks or risks to the water supply."

Researchers and affiliations

B. He, M. Li, L. H. C. Chua, C. Liu, Z. Xing, W. Du
Nanyang Technological University, Singapore

L. Chen
Hong Kong University of Science and Technology, China

E. Hans
PUB Singapore

Contact

Bingsheng He; BSHE@ntu.edu.sg

Covering all bases of urban water management

Multidisciplinary research at Singapore's Aquatic Science Centre is examining new and natural ways to understand, treat and manage the country's water resources

Fig. 1: The Aquatic Science Centre at Sungei Ulu Pandan, Singapore, is a state-of-the-art green building that facilitates research into, and promotes public awareness of, urban water management

Fig. 2: A variety of tropical plant species can simultaneously beautify and purify Singapore's canals

Stormwater collected through a network of canals, green roofs and reservoirs is an important supply of water for Singapore. Contaminants can accumulate in this water, so cost-effective and efficient management tools are used to enhance water quality. To improve current treatment measures, a multidisciplinary research team in Singapore is investigating how the structure of the aquatic environment and the organisms inhabiting it can enhance water quality in a low-energy manner. The team, led by Vladan Babovic and Sanjay Swarup at the Singapore–Delft Water Alliance along with Arthur Mynett of Deltares, the Netherlands, is conducting research at the Aquatic Science Centre (ASC) (Fig. 1), in partnership with PUB Singapore.

In a 4-year programme, the team initially monitored some 50 water-quality parameters of water collected from the Sungei Ulu Pandan catchment. Despite collecting runoff from various land-use types, water quality was within the allowable limits of Singapore's National Environment Agency (NEA), so acceptable for all parameters. The measurements also showed that industrial areas had higher values for aluminium and mercury than residential areas, where levels of copper, zinc and organic pollutants, such as naphthalene and toluene, were more significant. Further, the researchers found no evidence of nutrient-rich runoff from fertilizers in the catchment.

The team also investigated how plants and microbes could help improve water quality. Landscaping with species of plants that act as biological filters—by naturally cleaning the water as it flows past—is an area showing particular promise. The researchers found that *Epipremnum aureum*, commonly known as the money plant, remediates bisphenol A (BPA), an endocrine-disrupting chemical, and the woody plant species *Ficus microcarpa* removes heavy metal contaminants. Landscaping with these species would serve a dual purpose (Fig. 2). "Judicious selection of plants and their planting density would help to create aesthetic ecological habitats in current concretized canals," explains Babovic.

Another promising area is the use of biosorbents—dead organic matter from bacteria, fungi, algae and food waste—to remove metals, dyes, pesticides and other organic contaminants. Studies of various green roof set-ups have shown that some designs contribute nutrient (nitrates and phosphates) and metal (light and heavy metals) pollutants. According to Babovic, using biosorbents would help remove these dissolved contaminants. "Crab shell and *Sargassum* (seaweed) have proven to be good biosorbents to remove heavy metals in our studies." The team is planning to apply these findings in an integrated fashion and to test some of these results in the real world.

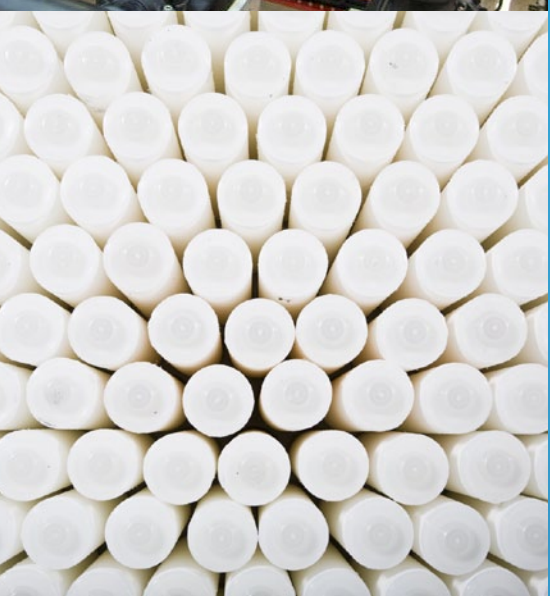
Researchers and affiliations

V. Babovic, S. Swarup, A. Mynett, S. Reuben, P. Han, U. M. Joshi, V. Kuppusamy, N. Pham, A. Biswas, T. Vergroesen, A. Wijdeveld, E. Penning, C. K. Yeo, C. K. Mynampati, N. N. Naing, G. Saxena, J. Cornelisse, P. Ng, P. Kumar, H. Tan, H. K. Lee, B. Ong, R. Balasubramanian, R. Uittenbogaard
Singapore–Delft Water Alliance

A. Mynett
Deltares, the Netherlands

Contact

Vladan Babovic; sdwhead@nus.edu.sg



Membrane Technology

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

The NEWater demonstration plant, commissioned in May 2000, uses microfiltration, reverse osmosis and 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 optimizing membrane processes for water treatment and used water treatment processes.

Membrane uses less energy to clean water

Improved filtration technology is helping to lower the costs of delivering a reliable water supply

Fig. 1: A unit of the new membrane bioreactor

Fig. 2: The new membrane bioreactor system test-bedded at the Ulu Pandan Water Reclamation Plant

Singapore is a small island nation with few natural water resources. Consequently, used-water treatment plants must occupy as little space as possible, while meeting the growing needs of industry and a booming population. In collaboration with PUB Singapore, researchers from Singapore and Japan have successfully developed and test-bedded a compact purification system that can process high volumes of water using less energy than existing systems.

Since the late 1990s, Singapore has recycled municipal used water in a two-stage process to produce high-grade reclaimed water—dubbed NEWater—that is ideal for industrial use. After the used water is filtered to remove hair and other large suspended solids, it is fed through a membrane bioreactor (MBR). This contains microorganisms that break down organic contaminants, and a membrane that filters out the accumulated sludge. The filtered water then passes through a second membrane, where a reverse osmosis process removes soluble components such as nitrates, phosphorus compounds and other non-biodegradable organic substances.

Although MBRs are more compact and produce cleaner water than older treatment technologies, they are more expensive to operate. Reducing the reactor's energy consumption is a vital way to cut costs, says Takanori Itonaga of MRC Rensui Asia Ltd, based at the PUB WaterHub research centre.

Almost half of the energy is used to bubble air through the reactor to prevent membrane fouling, so Itonaga and his colleagues tested a new MBR that requires less air (Fig. 1). The team installed a compact MBR with a polyvinylidene difluoride membrane, made by Mitsubishi Rayon of Japan, at Singapore's Ulu Pandan Water Reclamation Plant (Fig. 2). This MBR has an effective area of 320 square metres, with a 40% higher membrane-packing density than the existing MBR.

They found that each square metre of membrane could filter about 30 litres of water per hour, with 70% less air than before. This resulted in a 40% reduction in estimated energy demand to 0.37 kWh per cubic metre of water.

In previous work, Itonaga and colleagues had found that this membrane provided high-quality water that did not affect the performance of the reverse osmosis stage, particularly when chloramine was used as an additive to prevent biofouling of the second stage.

According to Itonaga, the results demonstrate that the new membrane is ready for use in other MBR facilities in Singapore. "We believe MBR is the key technology for the NEWater process," he says, adding that with further research, the next generation of MBRs should actually be able to generate energy from used water.

Researchers and affiliations

T. Itonaga
MRC Rensui Asia, Singapore

S. Kitagawa, Y. Oda, M. Sasakawa
Mitsubishi Rayon, Japan

T. Adachi
Nippon Rensui, Japan

C. B. C. Raj, K. A. Kekre
PUB Singapore

Contact

Takanori Itonaga; itonaga_takanori@mg.rensui.co.jp

Fighting filtration foul play

Removing membrane-clogging particles from water filters has become easier, thanks to detailed studies of organic pollutants

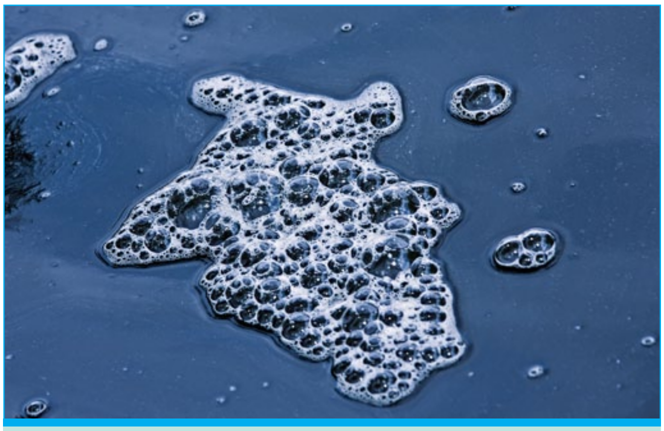


Fig. 1: Removal of organic contaminants from water by filtration is possible, but build-up of fouling layers on filter membranes causes enormous difficulties

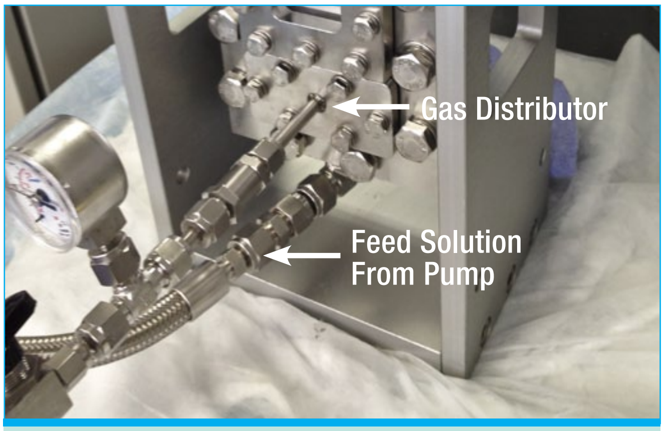


Fig. 2: The two-phase fouling control method uses air bubbles to enhance shear stress over the membrane surface, which effectively reduces the build-up of fouling layers

Filtration techniques have helped produce potable water for hundreds of years. Recently, engineers have turned to nanofiltration membranes—smooth, polymer thin films with nanometre-scale pores—to remove low-level pollutants from surface and ground water (Fig. 1). But the efficiency of these filters is offset by the tendency for the membrane surfaces to become clogged with accumulated layers of 'foulants'. At water treatment plants worldwide, this type of fouling increases costs and reduces water quality.

Chuyang Tang and colleagues from Nanyang Technological University, Singapore, have now discovered that oppositely charged organic contaminants, such as polysaccharides and proteins, play major roles in generating foulant layers. Such pollutants produce foulant 'cakes' that stick to filter membranes under a range of operating conditions. These insights have led to development of a revolutionary 'two-phase flow' method that uses air bubbles and a process known as ultrasonication to mechanically clean membrane surfaces (Fig. 2).

Membrane fouling is governed by complicated relationships between solution chemistry, filter properties and hydrodynamic flow rates. To date, however, linking the behaviour of organic pollutants to foulant growth has stymied researchers. Tang and colleagues resolved this problem by systematically varying the proportions of negatively charged sodium alginate and positively charged lysozyme molecules—sugar and protein macromolecules that represent the agglomerations frequently found in contaminated used water.

When the team examined used water contaminated with one type of macromolecule, they saw that the flux through a nanofiltration membrane remained steady and remained unblocked for hundreds of hours. Adding a small amount of lysozyme to alginate-contaminated feed water reduced the flux by 50% after a few hours.

The researchers found that increasing the proportion of lysozyme in the used water triggered greater build-up of foulant layers on the membranes. But irrespective of the pollutant concentration, the chemical structure of the foulants remained unchanged—a nearly equal ratio of lysozyme to sodium alginate. Tang explains that the interactions between the organic contaminants are so strong that they precipitate rapidly, which is similar to scaling by inorganic minerals.

Identifying which factors produced foulant layers inspired the team to develop new hydrodynamic procedures to limit membrane fouling, such as a two-phase flow device. In addition, the research team is working with European partners to produce water chemistries that disrupt organic agglomeration and improve filtration lifetimes. "Combining the two approaches is most effective," says Tang, "and the initial results are encouraging. We hope to patent the technology soon."

Researchers and affiliation

Y.-N. Wang, C. Y. Tang, S. R. Gonzalez-Avila, X. Huang, P. A. Quinto-Su, T. Wu, C.-D. Ohl
Nanyang Technological University, Singapore

Contact

Chuyang Y. Tang; CYTang@ntu.edu.sg

Catching contamination quickly

An ultrasonic detection system may help limit the damage inflicted by bacterial biofilms to water-processing plants

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Fig. 1: The accumulation of bacteria from unprocessed water can severely undermine the purification process

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Fig. 2: Rising pressure in filtration systems can indicate biofilm formation, but such warnings often arrive too late to prevent serious contamination

Whether purifying used water or desalinating seawater, water-processing facilities are in constant danger of blockage owing to the accumulation of microbes in the form of filter-clogging biofilms. Biofouling becomes detectable when pressure builds within the filtration system, but such warnings often arrive too late. "These changes may only become evident when fouling has progressed through the plant, and they are crude and insensitive indicators of a developing problem," explains Anthony Fane of Nanyang Technological University, Singapore.

As director of the Singapore Membrane Technology Centre (SMTC), Fane is helping PUB Singapore to devise early warning systems for biofouling. Ideally, these should be minimally disruptive of existing water-handling processes. Fane and colleagues are exploring strategies that involve diverting small amounts of raw water into a parallel 'canary cell' sensor—providing early warning of danger, like the canaries coal miners once relied on to detect poisonous gases.

Among the most promising potential solutions is a technique called ultrasonic time-domain reflectometry (UTDR). This technique measures the time required for sound waves to bounce off different surfaces in the water filtration system, generating a layered 'map' of filtration membranes in a manner similar to how bats use reflected sound to visualize their surroundings in the dark.

In principle, when layers of fouling material accumulate on a water-filtration membrane, UTDR should detect these as an additional 'echo' that arrives slightly sooner than the echo from the membrane itself. However, Fane notes that UTDR detection had previously proven successful only with inorganic fouling, not with microbes. "UTDR has difficulty 'seeing' biofilms because they have similar acoustic properties to water," he says. "Our idea was to enhance the acoustic properties of biofilms by intermittently injecting inorganic material that would [settle] on top of the growing biofilm and provide a reflected acoustic signal."

This concept proved effective: Fane's team found that periodic injections of silica into the canary cell dramatically enhanced detection of these previously invisible contaminants. "Our researchers could monitor biofilm height, obtaining values similar to those from membrane autopsies," he says. Importantly, these silica injections do not impair bacterial growth, ensuring that canary cell readings accurately reflect biofouling levels.

Fane believes this system is almost ready for pilot-scale implementation, giving the SMTC team a critical opportunity to test UTDR in 'real-world' conditions and learn how to translate sensor readings into actionable reports for facility staff. "This will involve modelling and experimentation over a range of operating conditions," explains Fane.

Researchers and affiliations

V. Sim, T. H. Chong, A. Yeo, W. B. Krantz, A. G. Fane, S. R. Suwarno
Nanyang Technological University, Singapore

J. Cen, H. G. L. Coster
University of Sydney, Australia

Contact

Anthony G. Fane; a.fane@unsw.edu.au



Network Management

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

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

Flow monitoring gets an acoustic boost

Ultrasonic technology makes for effortless detection of flow and sediment problems in complex pipe networks

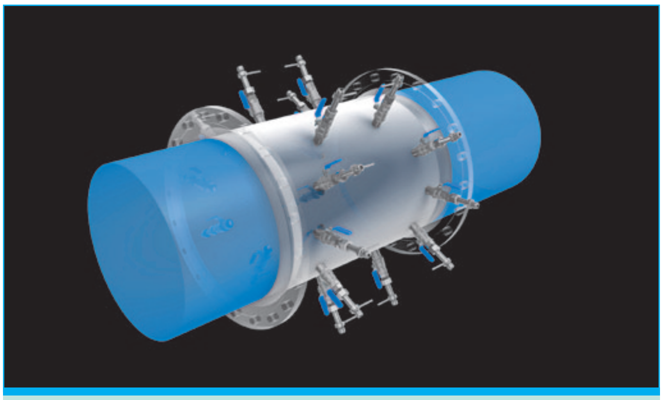

Fig. 1: A schematic representation of the ReVision flow meter, which uses ultrasonic sound waves to measure fluid speeds in entire pipe networks from a single location

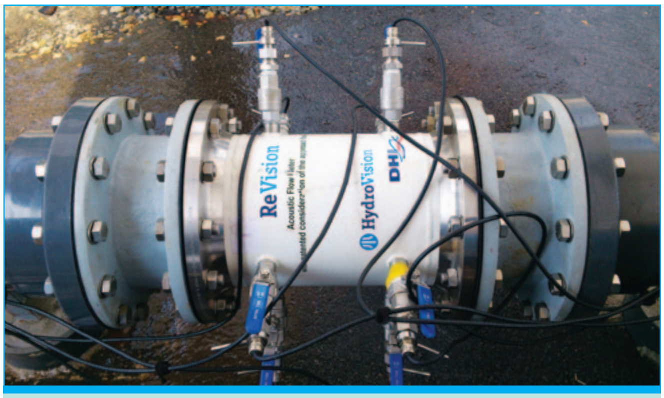

Fig. 2: An actual ReVision flow meter applied to a ductile uPVC pipe water network

A new start-up company, HydroVision Asia, supported by PUB Singapore and Singapore's Environment & Water Industry Programme Office (EWI), has developed technology that promises to transform the multi-million dollar marketplace for flow meters. The technology, called 'ReVision', uses ultrasonic sound to measure water flow in pipe networks with greater precision and lower costs than existing methods. This acoustic flow meter can also monitor water for abnormal levels of suspended sediment.

Flow monitoring is a critical procedure at facilities such as water treatment plants, hydroelectric dams and irrigation networks; but, detecting how fast a fluid flows through interconnected pipes with curved and branching sections is difficult. Most flow meters need long, straight segments to take accurate measurements. Space constraints, however, often lead to errors that require multiple meters and more expense to resolve.

ReVision solves this problem by combining acoustic technology with software reconstruction techniques to measure network flow from a single position (Fig. 1). Short ultrasonic pulses first measure water speed and direction. The meter then correlates this data with predetermined conduit parameters that results in reconstructing the whole flow velocity profile across the pipe. Thomas Hies, managing director of HydroVision Asia, explains that this setup is exceptionally reliable because its non-intrusive acoustic sensors lack moving parts (Fig. 2).

A PUB–EWI-funded project enabled HydroVision Asia to also convert their acoustic technology into a sediment transducer. Events such as tropical storms can cause high sediment loads to enter distribution systems. Automatic particle monitoring systems could drastically reduce costs associated with handling such loads, since most sediment detectors are labour intensive, requiring detailed calibration or water-sampling procedures.

HydroVision Asia's sediment transducer uses acoustic backscattering signals to measure sediment loads without resorting to time-consuming calibrations. It causes high-frequency sound bursts to ricochet off suspended sediments, and then analyses the resulting signals with software algorithms to rapidly and precisely assess particle size and concentration. Hies notes that although this technology is still under development, no device like it exists commercially—providing an opportunity to develop a new market segment.

Currently, HydroVision Asia is combining its flow meter and sediment transducer into an 'acoustic mass meter' that also measures suspended sediment concentrations. Integrating the meters into a single, maintenance-free design presents an attractive choice for industries upgrading to ultrasonic technology, explains Hies. "Our calibration-free approach is very user friendly and makes [reliable and] accurate measuring products directly available to consumers," he says.

Researchers and affiliations

T. Hies
HydroVision Asia, Singapore

J. Skripalle
HydroVision, Germany

L. Yanyan, H.-H. Nguyen, C. H. Nah, L. Jian
DHI Water & Environment, Singapore

Contact

Thomas Hies; t.hies@hydrovision.sg

Mathematical model cracks pipe problem

Simulation aids understanding of leakage from used-water pipes

Fig. 1: Singapore sits above a network of utility pipes, including used-water pipes

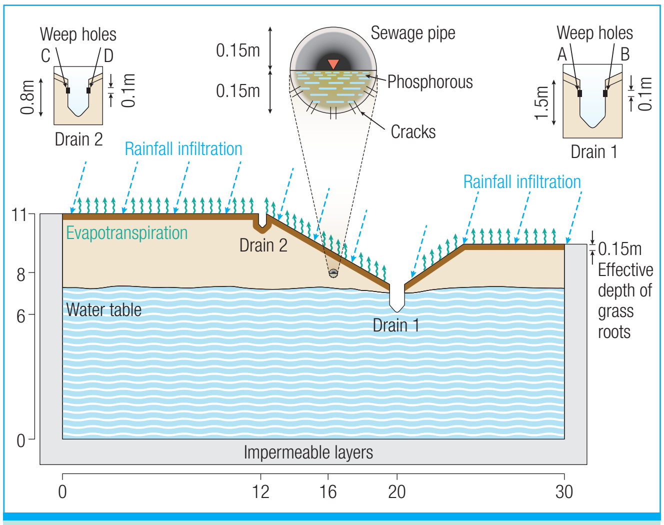

Fig. 2: A schematic diagram of the two-dimensional COMSOL conceptual model

Beneath Singapore's streets lies a network of utility pipes, including used-water pipes (Fig. 1). Over time, these pipes may deteriorate and crack, allowing used water to leak and mix with groundwater. Although Singapore does not use groundwater as a water source, its contamination could lead to the pollution of waterways and reservoirs.

PUB Singapore maintains about 3,400 kilometres of public sewers island-wide. It has an ongoing programme to check and repair old sewers using trenchless technology, in order to ensure the structural integrity and operational reliability of the system. Over the last 14 years, PUB has rehabilitated around 1,000 kilometres of public sewers.

Researchers at the National University of Singapore (NUS), funded by PUB, have applied a mathematical model to examine the hydrologic interactions between leaking used water pipes, groundwater and 'weep holes' in stormwater drains. The model was developed using a commercially available software product called COMSOL, and it sheds light on the local-scale migration of used-water pipe leaks.

Working with Jiangyong Hu, an environmental scientist at NUS, the team ran their simulation of a two-dimensional conceptual model of a virtual used-water pipe that is located above the water table and is shallower than an adjacent stormwater drain (Fig. 2). The drain's small weep holes allow groundwater to seep in from the surrounding soil when it is saturated with water.

The simulation results showed that in years of relatively little rain, the water seeping into the stormwater drain tends to be of poorer quality. Additionally, cracked used-water pipes are also more prone to leaking when surrounded by dry soils. Heavy rains quickly force groundwater through the weep holes, thus diluting and flushing the accumulated leakage in the subsurface.

The NUS team also found that even after the pipe is repaired, leakage to the stormwater drain may cease after several months or years, depending on the leakage duration. "Even after sewage pipe rehabilitation, the accumulated mass in the aquifer takes significant time to naturally deplete at a small site," says Hu. As such, the researchers recommend that water quality monitoring programmes for stormwater drains should continue for at least a year after the pipes are repaired.

Calibrating and verifying the model with local field data could improve the predictions and it may also be applicable to other cities, they add. "The findings from this project will enhance PUB's understanding of the processes and factors affecting migration of used water pipe leaks," says Hu.

Researchers and affiliations

D. K. Ly
Brandenburg University of Technology, Germany

J. Hu, T. F. M. Chui
National University of Singapore

Contact

Jiangyong Hu; esehuiy@nus.edu.sg

On alert for remote water-supply contaminants

Water quality monitoring devices based on piezoelectric sensors rapidly detect chemical and biological pollutants in Singapore's raw water resources

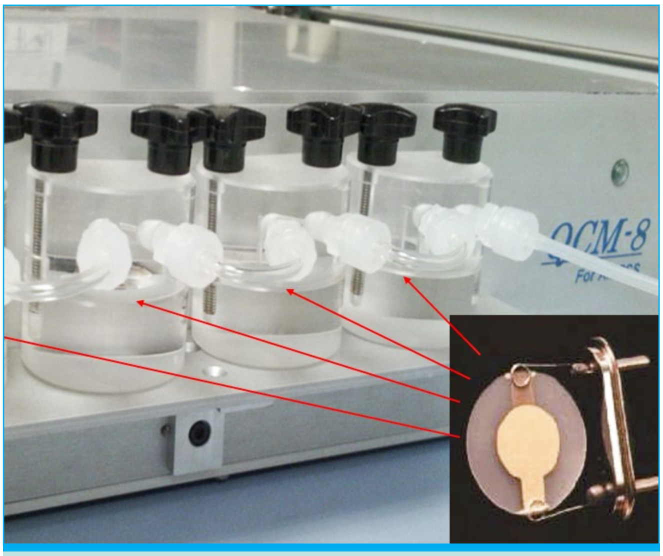

Fig.1: Quartz crystal microbalance (QCM) sensors (inset) use piezoelectricity to detect pollutants in water samples (main image)

Fig. 2: Water quality monitoring devices based on piezoelectric sensors could be deployed in Singapore's reservoirs for remote sensing of contaminants

From its used-water recycling systems to its rivers and reservoirs, PUB Singapore monitors a range of water sources for potential contaminants. A versatile system for *in situ* pollutant monitoring of these diverse water supplies is being developed by a research team in Singapore led by Sam Li at the National University of Singapore. The team is collaborating with PUB on a prototype device capable of detecting multiple chemical and biological pollutants at trace concentrations.

At the heart of the researchers' device is a set of piezoelectric quartz crystal microbalance (QCM) sensors. When a piezoelectric quartz crystal is placed between two electrodes that generate an alternating electric field, it oscillates at a characteristic frequency. If anything attaches to the crystal's surface—such as a pollutant—the extra mass will shift the oscillation frequency detected by the QCM sensor.

"The advantage of using piezoelectric devices as sensors for pollutants in water is their ultrahigh sensitivity and flexibility for modification to detect multiple pollutants," says Li. To turn QCM sensors into water quality monitors, Li and his team coated the quartz crystals with functional agents that selectively capture particular pollutants from a water sample. For example, they employed a protein-based surface coating to which pathogenic bacteria, such as *Escherichia coli* and *Salmonella enterica*, will stick. If these bacteria are present, the QCM sensor will detect the crystal's oscillation shift and then sound the alarm that a pollutant is present.

The team tested the device's performance using water samples spiked with traces of bacteria (Fig. 1). They showed that, within 5 minutes, they could simultaneously detect the presence of several pathogenic bacterial strains in a sample.

In a separate set of tests, the researchers demonstrated the system's adaptability. They showed that by coating their sensors with metal-targeting DNA-based probes, they could quantify heavy metal ions such as mercury, lead and copper down to concentrations of parts per billion. Importantly, the sensors selectively detected these metals in the presence of ten other metal ions, thereby avoiding false–positive results.

In the next step, the team will work with industry collaborators to validate the device's performance using a test bed (Fig. 2), says Li. From these results, the prototype will be further optimized for *in situ* testing. Li and his colleagues have already demonstrated that their device can wirelessly transfer its water sampling results, an essential step towards water quality sensing in remote locations.

Researchers and affiliation

S. F. Y. Li, H. Wu, H. Y. Li, H. B. Teh, M. H. Liu, J. Y. Lin
National University of Singapore

Contact

Sam F. Y. Li; chmlifys@nus.edu.sg

Used Water Treatment

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

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

Filter-blocking bacteria get the message to scatter

Naturally occurring compounds can 'hack' the communication mechanisms of bacteria that accumulate in water purification systems

Fig. 1: A halogenated furanone, derived from the red alga *Delisea pulchra* (pictured), helps disrupt quorum signals generated by biofilm-forming bacteria

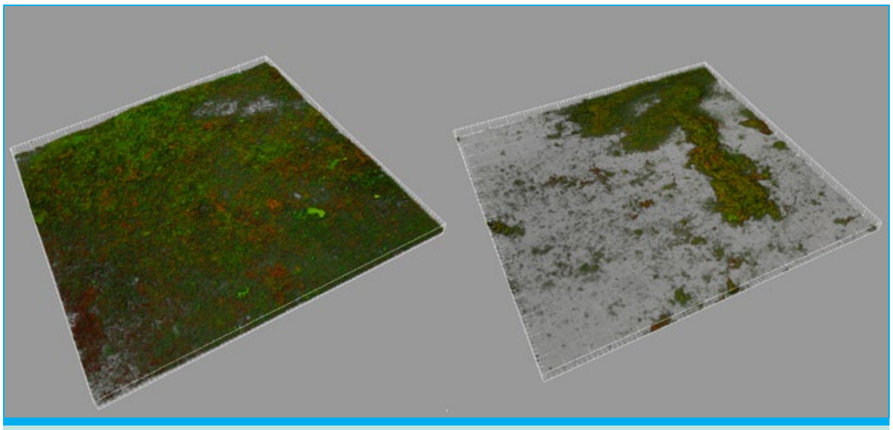

Fig. 2: Reverse osmosis membranes, untreated (left) and treated with nitric oxide, NO, (right) after washing with a standard industrial disinfectant. Disinfection efficiency was notably improved by NO treatment, reducing the quantity of toxic chemicals needed to disperse the biofilm

Water purification plants are hindered by the steady accumulation of bacterial biofilms—the slimy layers of microbe-laden muck clog filtration membranes and undermine operational efficiency. This problem is especially critical for Singapore, which is becoming increasingly dependent on desalination and used-water reclamation facilities to produce adequate supplies of clean, potable water.

Staffan Kjelleberg and Scott Rice of Nanyang Technological University (NTU), Singapore, recently teamed up with Diane McDougald, also at NTU, to devise smarter methods for disrupting biofilms before they become problematic. The work is being done on behalf of Singapore's Environment & Water Industry Programme Office (EWI) and PUB Singapore. Existing strategies employ chemicals to kill bacteria without damaging filtration membranes, but the team is looking instead to manipulate the natural communication systems used by bacteria to 'trick' microbes into scattering.

One approach employs algal-derived compounds known as furanones (Fig. 1) that block so-called 'quorum' communication signals, which growing populations of bacteria normally produce to stimulate biofilm formation. When combined with existing antimicrobials, furanones have proven highly effective at preventing biofilm accumulation. Rice notes that their chemical properties also prevent them from crossing filtration membranes into purified water. "Additionally, these compounds are biodegradable and would not be expected to accumulate in the environment," he says.

The team is also seeking to exploit a bacterially produced signal, the chemical nitric oxide (NO), which microbes normally release as a cue for dispersal rather than accumulation. "The hypothesis is that the production of NO acts as a signal that the biofilm is experiencing sub-optimal growth conditions such as overcrowding, leading to reduced oxygen access," says Kjelleberg. "This ultimately results in the release of bacteria from the biofilm." In their studies thus far, Kjellerberg and his team have found that the presence of NO counters biofilm formation for almost all bacterial species tested (Fig. 2). Already, they have demonstrated the effectiveness of NO either alone or in the presence of other microbicides in a pilot-scale system.

Further laboratory work will be necessary before scaling up to broader deployment. For example, the team has yet to determine how effective these various treatments are at preventing fouling caused by the sticky layer of polymers secreted by biofilm-forming bacteria, and whether they perform as well with real-world source water containing diverse bacterial communities. However, Kjelleberg sees the process advancing rapidly, allowing them to identify suitable treatment strategies in the near future.

Researchers and affiliations

S. Kjelleberg, S. A. Rice, D. McDougald
Nanyang Technological University, Singapore

R. Barnes, United Kingdom; R. R. Bandi, India; W.-S. Wong, Malaysia; X. Chen, China; J. Luo, China; Q. Zhang, China; X. H. Tan, Singapore; F. Chua, Singapore
Nanyang Environment and Water Research Institute (NEWRI), Singapore

Contact

Staffan Kjelleberg; s.kjelleberg@unsw.edu.au

Used water reclaimed in a single step

A streamlined process by which industrial used water is cleaned for re-use promises to make water reclamation more efficient

Fig. 1: The heavy demand for water in oil refining can be reduced by reclaiming used water

Fig. 2: Testing the membrane distillation bioreactor for treating used water in a pilot plant installed at an oil refinery

Oil refining and related heavy industries consume vast quantities of water in various processes, including equipment cooling (Fig. 1). In Singapore, many industrial facilities have cut water consumption by reclaiming used water. Today's industrial used-water reclamation technology requires two separate treatment steps to generate water clean enough for re-use. An alternative approach that reclaims used water in a single step is currently being pilot-tested by Fook-Sin Wong at the Nanyang Technological University (NTU), Singapore, and his colleagues, in collaboration with PUB Singapore. Wong explains that their approach has two advantages over existing reclamation processes for used water destined for re-use in industry: it has a smaller physical footprint, and it should also be more energy efficient.

The approach taken by Wong's team is a refinement to the first step of the conventional used water treatment process; it can improve water quality to the extent that the second step becomes redundant. Currently, industrial used water is initially treated using membrane bioreactors: microbes digest organic matter within it, leaving water and solid sludge that can be separated using a hydrophilic membrane. However, various impurities in used water, which render it unsuitable for industrial re-use, can also cross this membrane. Thus, the water must be further treated by reverse osmosis.

Previous research at NTU has shown that switching the hydrophilic membrane for a water-rejecting hydrophobic one reduces the amount of impurities that cross into the product water stream. Although water cannot cross the membrane, water vapour can pass through unimpeded. The researchers used industrial waste heat to raise the temperature of the used-water feed, generating enough vapour to achieve a steady water flux across the membrane.

Wong says that by using waste heat, membrane distillation bioreactors should cut the amount of electricity required for used water reclamation. The conventional process consumes 1.3 to 1.4 kWh of electricity per cubic metre of water produced. The single-step process should use less than 1.3 kWh per cubic metre of water.

Wong and his colleagues have been testing the technology at a 1.2 cubic metres-per-day pilot plant installed at an oil refinery (Fig. 2). A series of tests on different membrane materials revealed that commercial flat sheet Teflon (PTFE) membranes give the best balance of water flux and product water quality.

The current pilot project is due to be completed at the end of March 2013, Wong notes. If the researchers and their industrial partner are satisfied with the performance of the membrane distillation bioreactor, they will test the technology at a larger demonstration scale.

Researchers and affiliations

F.-S. Wong, N. Wai, J. F. Li, E. K. Tan
Nanyang Technological University, Singapore

A. N. Puah, J. S. S. Chin
PUB Singapore

Contact

Fook-Sin Wong; wongfs@ntu.edu.sg

Self-cleaning filters improve water screening

In pilot trials at a water reclamation plant in Singapore, self-cleaning, micro-screening filters remained clean and unblocked under optimized operating conditions

Fig. 1: The left side of this rotating drum screen is almost completely blocked with debris, and so needs to be cleaned

Fig. 2: The double-action cleaning mechanism of the Baleen Filters system keeps the screens free of debris and blockages so that they can operate continuously

Removing suspended solids and other material is a crucial first step in treating municipal used water. At Singapore's Ulu Pandan Water Reclamation Plant (UPWRP), the Membrane Bioreactor Plant (MBR) uses rotating drum screens for this purpose but they become clogged with debris such as cotton, rags, hair and fibres (Fig. 1).

Rotating drum screens are cylindrical with varying screen sizes; used water flows into them, and as the drum rotates, suspended solids are separated from the water as it flows through the screen. At UPWRP, automatic washing of the screens is ineffective at dislodging this debris, so one of the two drum screens must be cleaned manually each week, leaving the plant running at only 50% capacity.

Utilizing a test-bedding pilot plant at UPWRP, researchers from PUB Singapore and the company Baleen Filters have demonstrated that the screens in Baleen's filters remained unblocked during normal operations (Fig. 2).

In the pilot trials, the researchers exposed the Baleen filter system to the same in-flow stream as that ordinarily supplied to the rotating drum screens. The 1-millimetre-square screen of the Baleen filter system was 4 times finer than that of the rotating drum screens, which have 2-millimetre-square screens. Once installed, the researchers optimized filtration for maximum separation by adjusting the wash-water pressure and the timing of the cleaning mechanism.

Not only did the Baleen filter screen remain clean and unblocked, it also removed more solids from the waste stream than the rotating drum screens because of its finer screen rating. As such, Baleen's micro-screening system potentially complements coarser screening technology in membrane-filtration systems. Utilizing Baleen's filtration technology at the MBR plant would allow it to operate continuously at its full capacity since it does not require manual cleaning.

"The Baleen filter system is specifically designed for screening suspended matter from water and other process streams, and is protected by international patents," explains a company representative. "It is based on a simple, yet ingenious 'double-act' of high pressure, low volume water sprays: material trapped by the filter is dislodged, and then swept away for collection."

Baleen Filters, based in Australia, states that its filters are also flexible in their potential uses. In general, drum screens are used on inflow waters at the start of the water treatment process. Baleen filters can not only be used on the inflow, but also at other points in the total municipal used-water treatment process, such as sludge thickening and final polishing.

Researchers and affiliations

R. Crewdson
Baleen Filters, Australia

Shaikh Mohd Riad
PUB Singapore

Contact

Robert Crewdson; robert@baleenfilters.com

Water Quality and Security

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

Microbe detection under the microscope

Establishing an interdisciplinary toolkit will help Singapore detect the full suite of microbes that can harm human health in multi-use water sources

Fig. 1: Implementing a unified sampling protocol in the field for all major groups of microbes would greatly improve source water quality assessment

Fig. 2: Addition of internal standards, such as fluorescence-tagged bacteria, will aid quality control of testing methods

Accurate, reliable and timely assessment of water sources is essential to protect human health. Current methods for monitoring water quality can be improved to better fulfil recommended management tools, including water safety plans (WSPs). To expand Singapore's capacity for detecting harmful microbes in its source waters, Siao Yun Chang from PUB Singapore, and collaborators in New Zealand, the United States, and Puerto Rico examined over 2,000 medical, chemical, engineering and microbiological papers. They have uncovered several promising technologies.

When evaluating microbial detection methods, they sought ways to improve sample processing and testing. They also prioritized methods based on their reliability, field-readiness and efficient throughput. "There is a bottleneck in processing large volumes of water—a long time is required for sample processing and recovery rates are variable," explains Chang. "And, there is a need to improve specific internal standards to assess the efficiencies of many microbial methods."

Recovering microbes efficiently from source water is a critical first step, and high-throughput filtration systems may greatly improve sample concentrations. The researchers therefore plan to trial hollow-fibre ultrafilters and microfabricated filters in various configurations, and using only a small sample volume (10 litres), to produce a unified sampling and monitoring protocol for bacteria, viruses and protozoans (Fig. 1).

Standard protocols used currently to identify water contaminants rely on time- and labour-intensive bacterial culture. Genetic methods could enhance or complement these protocols. Chang and colleagues therefore propose to trial various genetic methods that will improve the speed and efficiency of detection. One method in their sights is isothermal amplification, which is similar to polymerase chain reaction (PCR) but simpler to implement and less sensitive to contamination.

Chang and his team also propose implementing quality assurance measures. Chang explains that they have identified some specific internal standards for key microbes that will allow researchers to assess the actual efficiency of each detection method. By adding tagged samples of known concentrations of surrogate, or inactivated, microbes to water samples, researchers could verify whether a given testing protocol is operating properly.

Chang and colleagues will trial these new methods against a list of target microbes including *Escherichia coli* (Fig. 2), Norovirus and *Cryptosporidium*. "We hope that a combination of the new microbial methods and the current approved methods will provide more robust microbial data on our source waters," says Chang. "These data will support water utilities such as PUB in making informed decisions on managing catchment and treatment of fresh and used water, ensuring safe water supplies and protecting public health."

Researchers and affiliations

S. Y. Chang, M. V.-M. Wong, W. L. Teng
Water Quality Office, PUB Singapore

J. Bartram, M. Sobsey
University of North Carolina, United States

J. Love, M. Savill
Affordable Water Ltd, New Zealand

G. Toranzos
University of Puerto Rico, Puerto Rico

Contact

Siao Yun Chang; CHANG_Siao_Yun@pub.gov.sg

Phytoplankton light the way to quicker sorting

Development of techniques that rapidly identify toxic phytoplankton in Singapore's reservoirs could soon reduce the health risks posed by algal blooms

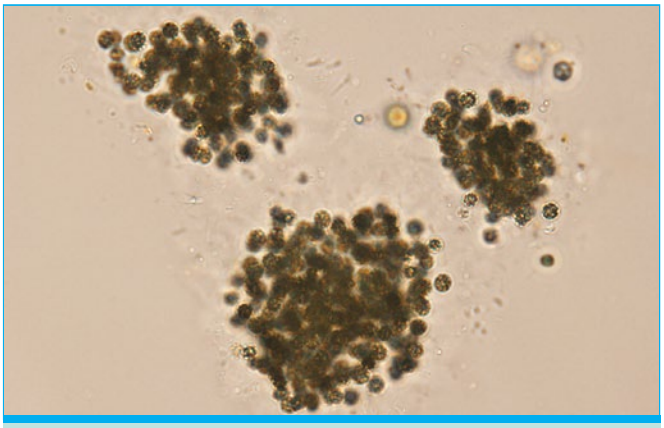

Fig. 1: Conventional identification of toxic phytoplankton that cause harmful algal blooms requires laborious microscope work

Fig. 2: Some of the algal blooms present in Singapore's reservoir system can pose a health risk if consumed, however, flow cytometry could be used to automatically distinguish between phytoplankton species

Distinguishing between different types of phytoplankton in water samples is a challenging task. Current methods for identifying and counting toxic phytoplankton, such as cyanobacteria, are time-consuming, prone to human error and require skilled technicians using microscopes.

To ameliorate these problems, scientists at the National University of Singapore, in collaboration with PUB Singapore, are developing automated methods to identify nuisance phytoplankton in Singapore's reservoirs. They have adapted a technique commonly used in biomedical sciences.

"Flow cytometry (FCM) is a process by which particles suspended in a fluid are counted, for example for the enumeration of cancerous cells," explains team leader Tsai Min Sin. "We have developed FCM techniques that distinguish between different genera of phytoplankton in our reservoirs."

FCM uses lasers to collect information on the light scattering and fluorescence of individual particles. This gives researchers a detailed breakdown of the size, shape, type and number of particles present in a fluid.

"Fluorescence corresponding to the wavelengths of different pigments can be used to distinguish between various types of phytoplankton and other suspended matter," Sin notes. "We also use labelled fluorescing probes that attach to particular genes, allowing us to identify toxin-producing particles in which natural fluorescence signals are not easily distinguishable from others."

FCM can scan a water sample in 15 minutes, whereas a microscope analysis can take up to 4 hours (Fig. 1). However, FCM requires accurate recognition protocols that relate different fluorescence signals to particular phytoplankton types. These relationships can vary across environments. Sin's team is adapting appropriate protocols for Singapore's waters.

"Although some phytoplankton fluorescence signals have been analysed in other countries, there is no reason to assume that the signals for a particular genus would be identical across regions," Sin explains. "Our work is important for addressing this gap."

FCM allowed the team to distinguish cyanobacteria in reservoir samples (Fig. 2), achieving an accuracy of over 95% for the common genus *Microcystis*. Previous studies may have underestimated levels of cyanobacteria because they are often too small to be detected in conventional microscope analyses. "Eventually, we would like to be able to achieve a level of population discrimination equivalent to conventional screening," says Sin.

Sin and colleagues have also developed FCM techniques that can distinguish between bleached and unbleached symbiotic algae that live in coral tissues. Further, their work on cataloguing the autofluorescence signals of phytoplankton taxa may eventually support large-scale applications, such as remote sensing of phytoplankton blooms.

Researchers and affiliations

Y. S. W. Yeo, C. S. Lee, T. M. Sin
National University of Singapore

C. Feng
PUB Singapore

Contact

Tsai Min Sin; tmssintm@nus.edu.sg

On the trail of sweet and persistent pollutants

A highly sensitive approach for monitoring previously uncommon pollutants will aid their removal from used water destined for reclamation

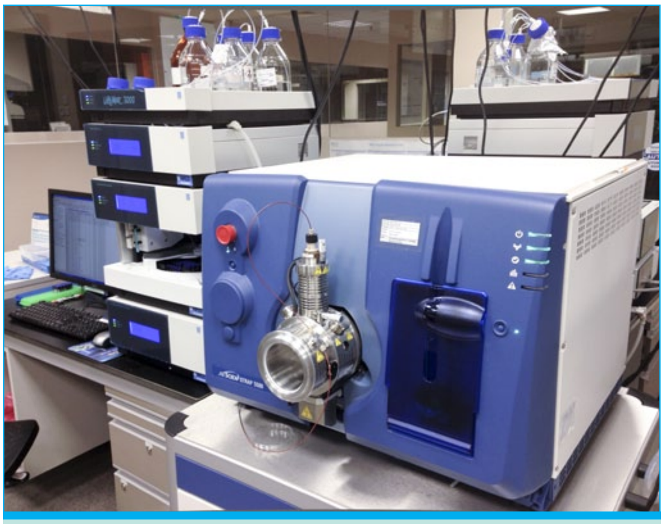

Fig. 1: Sample processing by solid phase extraction in the laboratory

Fig. 2: Singapore's Ulu Pandan Water Reclamation Plant

Artificial sweeteners and so-called 'perfluorinated' chemicals are increasingly being detected in used water owing to greater day-to-day usage. These contaminants persist and accumulate in the environment, and the perfluorinated chemicals are readily absorbed and stored in living plants and animals. To monitor the occurrence and fate of these chemicals in used-water treatment plants, researchers in Singapore have developed a system that detects these chemicals at low concentrations. Karina Gin at the National University of Singapore developed the approach in close collaboration with researchers at PUB Singapore.

Gin and her team based their approach on a highly sensitive analytical method known as 'liquid chromatography mass spectrometry in tandem mode'. Depending on the type of contaminant, they prepared their samples using one of two techniques. To quantify the concentrations of artificial sweeteners, they injected the sampled water directly into the instrument since these contaminants have high, and detectable, concentrations in used water.

To quantify the concentrations of perfluorinated chemicals, which occur at lower levels, the researchers first had to concentrate the samples. For this step, they used a technique known as solid-phase extraction to purify and concentrate used-water samples in a solid-packed cartridge that selectively retained the desired compounds only (Fig. 1). This extraction technique is essential because used water is a complex matrix that can generate a complicated final extract requiring extra processing steps, Gin notes.

By sampling water at different stages of the reclamation process, Gin and her team assessed the ability of the existing facilities at the Ulu Pandan Water Reclamation Plant to eliminate these contaminants (Fig. 2). Their tests for perfluorinated compounds revealed that the removal processes currently implemented at the plant do not remove the perfluorinated compound known as perfluorooctanoic acid. Only trace amounts of other soluble perfluorinated substances, however, remained in the water. The team's sampling also showed that, among the artificial sweeteners detected in used water, saccharin and cyclamate, but not acesulfame and sucralose, are eliminated using existing treatments. "These results suggest that extra treatment processes may be needed if we want to remove persistent artificial sweeteners," says Gin.

Gin's team is currently planning to generate a combined method that can measure these compounds in a single run to reduce analytical effort and resources and to improve the precision of data correlation. "We are also working on designing and setting up bench-scale reactors to test removal efficiencies for other emerging contaminants, including pharmaceuticals and personal care products," she adds.

Researchers and affiliations

K. Gin, V. T. Nguyen, G. Jie, Y. Luhua
National University of Singapore

A. Duarah, L. Lin
PUB Singapore

Contact

Karina Gin; ceeginyh@nus.edu.sg

Water Treatment

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

However, desalination is a high-energy-demand process and energy cost is the biggest impediment to viable commercial development. Singapore carries out innovative research and development aimed at reducing energy consumption for step-wise desalination and finding alternatives to reverse osmosis technology that can further reduce energy requirements. For 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.

Putting minerals back where they belong

Restoring essential elements to desalinated seawater improves the safety and efficiency of water distribution networks

Fig. 1: Untreated seawater reverse osmosis water can have deleterious effects on small metal-strip samples of ductile iron (left), cement-lined (centre) and cast iron (right) pipes

Fig. 2: Biological growth experiments reveal that remineralization of water protects pipes from corrosion but also provides a breeding ground for bacteria

In many regions, seawater desalination is vital for providing consumers with fresh drinking water. However, the reverse osmosis membranes used in this process to remove salt and other dissolved minerals produce water that is corrosive, unless it is remineralized, with calcium, for example. Jiangyong Hu from the National University of Singapore and her colleagues are collaborating with PUB Singapore to investigate remineralization options for water treated with the seawater reverse osmosis (SWRO) process.

Several methods exist to reduce the corrosiveness of SWRO water, including dosing with calcium-based inorganic minerals or by adjusting pH levels. But the long-term effects of remineralization on pipe network stability remain mostly unknown—especially in Singapore's tropical environment. Hu and her team have elucidated the precise conditions that reduce scaling and corrosion using three model materials: ductile iron, cast iron, and cement-lined ductile iron pipes.

The researchers explored various ways of treating SWRO water, ranging from no addition to simple pH adjustment and to treatment with several types of calcium and/or magnesium-based minerals. Hu explains that the minerals, in addition to providing key elements for human health and agriculture, are important for remineralization because they can restore the chemical 'hardness' of water, which reduces pipe corrosion.

After immersing small strips of the pipe materials for close to 500 hours in non-treated SWRO water, the team observed striking visual changes to the materials (Fig. 1). The ductile iron and cast iron samples corroded quickly, and the iron dust turned the water red. The cement-lined samples appeared intact; but, weight tests revealed that mortar leaching had occurred. Calcium treatments stopped these corrosive attacks in their tracks—the three different types of materials all retained most of their weight after exposure to buffered SWRO water.

Despite the success of their calcium remineralization experiments, the researchers found one drawback: calcium can affect the biological stability of SWRO water and promote the growth of biofilms on the materials (Fig. 2). Hu notes that calcium remineralization treatments must include proper bacterial control for them to be effectively applied to drinking water distribution systems.

Hu and her team's findings suggest that under tropical conditions, the cement-lined pipes provide the best protection against corrosive SWRO water, treated or not. This barrier slows the ion transfer reactions that lead to pitting and eventual degradation of metal pipes. Hu notes that lining metal pipelines with cement will reduce corrosion and improve water quality in tropical environments.

Researchers and affiliations

J. Liang, A. Deng, J. Hu, J. Zhang, C. N. Ong
National University of Singapore

R. Xie, M. Gomez
PUB Singapore

A. Adin
The Hebrew University of Jerusalem, Israel

Contacts

Jiangyong Hu; ceehujy@nus.edu.sg
Rongjing Xie; xie_rongjing@pub.gov.sg

Good vibrations for cleaner membranes

Combinations of vibrations and air bubbling can efficiently minimize membrane fouling in bioreactors

Fig. 1: Air bubbling, known as sparging, can help to reduce membrane fouling in submerged membrane bioreactors (SMBRs)

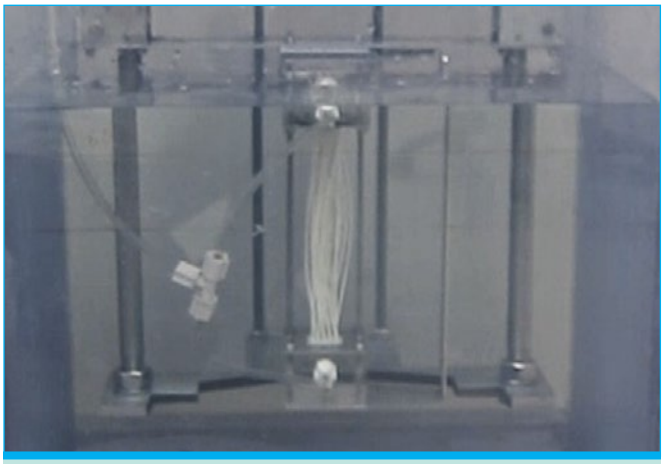

Fig. 2: Vibrating the membranes in the test tank (pictured), further reduced membrane fouling

Treating used water so that it can be recycled into NEWater, high-grade reclaimed water which is the pillar of Singapore's water sustainability, is an important task for the island nation. Submerged membrane bioreactors (SMBRs) are among the most useful technologies in the used-water pre-treatment process.

In an SMBR, microorganisms break down solids and dissolved materials in the feed water. The cleaned water then passes through a membrane, leaving the contaminants behind. Because the aptly named 'hollow fibre membranes' can be tightly packed to save space and cost, they are emerging as the membrane of choice for SMBRs. Hollow fibre membranes, however, regularly suffer from a build-up of foulants that reduces their efficiency and wastes energy.

Adrian Wing-Keung Law and colleagues at Singapore's Nanyang Technological University and the Singapore Membrane Technology Centre are working in collaboration with PUB Singapore to reduce SMBR membrane fouling. In a study of the hydrodynamics induced by various antifouling methods, they have found that employing a combination of air bubbling, or sparging (Fig. 1), and vibrating the membranes (Fig. 2) can be very effective.

"Air sparging is the main antifouling method used currently in SMBRs worldwide," says Law. "This oxygenates the water and provides fouling control." The foulant-removing shear stresses produced by sparging alone, however, are relatively weak, and the process consumes a lot of energy.

Law and colleagues therefore performed a series of experiments to examine the effectiveness of combining air sparging and vibrations to mitigate fouling. After trying several combinations of settings, they found that the best way to reduce fouling was by applying high-amplitude, and low-frequency vibrations, with some looseness in the fibres where they were bound to the mounting frame.

"Quantifying the hydrodynamics inside the reactors and linking them to the membrane fouling performance was challenging," says Law. "We used the advanced laser imaging technique called particle image velocimetry, as well as ultrahigh-speed photography. We also developed a new pressure-sensing approach for the task."

The team's findings are good news for the water industry, because inducing membrane vibrations consumes much less energy than air sparging. "With this improved understanding, new membrane modules coupling air sparging and vibration can be developed, with lower energy requirements," says Law. "Vibrational membrane modules without air sparging can also be deployed in situations where this process is not desirable, such as for anaerobic SMBRs—an important developing application." Law and his colleagues are continuing their research to determine the technical and economical feasibility of the concept for field implementation.

Researchers and affiliations

T. Li, A. W.-K. Law, M. Cetin, A. G. Fane, L. Xia, F. Zamani
Nanyang Technological University, Singapore

Nanyang Environment and Water Research Institute (NEWRI), Singapore

Contact

Adrian Wing-Keung Law; CWKLaw@ntu.edu.sg

Harnessing sunlight for desalination

A solar-powered water purification system tested in Singapore provides clean water from clean energy

Fig. 1: The memsys Clearwater prototype at Marina Barrage

Fig. 2: On a cloudless day, the sunlight in Singapore provides enough energy for desalination of seawater

A self-contained, solar-powered desalination system, designed to provide freshwater in remote locations or for disaster relief, has successfully completed a year of test-bedding at PUB Singapore's Marina Barrage facility (Fig. 1). The prototype is the result of collaboration between Fook Hoong Choo and his team at Singapore's Nanyang Technological University (NTU), and membrane distillation-technology company memsys Clearwater, based in Singapore and Germany. The trial represents the first demonstration of a memsys desalination module powered entirely by solar energy.

At the heart of the device is a novel process known as vacuum multi-effect membrane distillation (V-MEMD). Incoming seawater or used water is heated to generate water vapour, which is then drawn through a membrane by lowering the pressure on the far side. Once through the membrane, the now-pure water is collected and condensed. Energy recovery systems help to lower the module's overall power demands such that it can be driven by waste or solar heat. Additionally, the compact design fits within a shipping container for ease of transport to remote destinations.

For the Marina Barrage test, NTU researchers developed solar-powered systems to drive the V-MEMD system. Solar collectors gathered the thermal energy required to heat the water for membrane distillation, while photovoltaic panels generated electricity to power pumps and other electronic components.

As with any solar-powered device, the weather was a key factor in determining the module's productivity. When sunny, the system generated up to 40 litres of freshwater per hour under optimal operating conditions (Fig. 2). However, during the rainy season—when the weather on most days alternated between sunshine and cloud—the researchers could not collect enough solar thermal energy to heat water in the system's twin 500-litre feedwater storage tanks to the 80 °C required for desalination.

Based on the prototype's performance, the researchers proposed several improvements for future iterations of the system. For example, by incorporating extra valves between the tanks, the available solar energy could be used to heat the feed water in stages, meaning that some freshwater could still be produced on partly cloudy days. Additionally, they proposed the integration of a diesel generator into the system, using its output to power electronic components and its exhaust heat to warm the feed water.

"We plan to test these and other optimizations when we make a subsequent solar-desalination memsys system," says Niranjan Sarda, international sales director at memsys Clearwater in Singapore. The team is currently seeking partners with whom to advance the project.

Researchers and affiliations

K. Zhao, W. Heinzl, G. Lange, N. Sarda, S. Gomez Lavin, G. van Gendt
memsys Clearwater

F. H. Choo
Nanyang Technological University, Singapore

Contact

Niranjan Sarda; niranjan.sarda@memsys.sg

PUB Collaborators

Universities, Research Centres and International Organizations

Advanced Environmental Biotechnology Centre	Singapore
Agency for Science Technology and Research	Singapore
American Water Works Association	USA
Black & Veatch Global Design Centre for Water and Centre of Excellence for Desalination	Singapore
CDM's Neysadurai Technical Centre	Singapore
Center for Environmental Sensing and Modeling	Singapore
Central South University	China
Deltares	Netherlands
DHI-NTU Centre	Singapore
DVGW-TZW Water Technology Center	Germany
Eidgenössische Technische Hochschule Zürich	Switzerland
Flinders University	Australia
Global Water Research Coalition	Netherlands
IBM Centre for Intelligent Water Optimization and Control	Singapore
Imperial College London	UK
Institute of Environmental Science and Engineering	Singapore
KAUST Water Desalination and Reuse Centre	Saudi Arabia
KWR Watercycle Research Institute	Netherlands
Massachusetts Institute of Technology	USA
Nanyang Environment and Water Research Institute	Singapore
Nanyang Technological University	Singapore
National University of Singapore	Singapore
New Energy and Industrial Technology Development Organization	Japan
Ngee Ann Polytechnic Centre of Innovation for Environmental & Water Technology	Singapore
NUS-Environmental Research Institute	Singapore
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Sembcorp R&D Collaboration	Singapore
Siemens Water Technologies' Global Water R&D Center	Singapore
Singapore Centre on Environmental Life Sciences Engineering	Singapore
Singapore Membrane Technology Centre	Singapore
Singapore Polytechnic	Singapore
Singapore University of Technology and Design	Singapore
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Singapore-Peking-Oxford Research Enterprise for Water Eco-Efficiency	Singapore
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Water Utilities and Companies

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Pan Asian Water Solutions	Singapore
PulverDryer	USA
PWN Technologies	Netherlands
Rand Water	South Africa
Rehau Unlimited Polymer Solutions	Germany
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