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.

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

Let us help bring your innovations to fruition. Visit www.pub.gov.sg/ewi today to find out more about our schemes.
Welcome to the fifth issue of *Innovation in Water | Singapore*.

This issue looks at the ways in which Singapore is exploring sustainable solutions to meet its water needs, an expansion of the focus of earlier issues where we highlighted the important role played by PUB, Singapore’s national water agency, in driving innovation in water technologies. Issue Four, in particular, focussed on collaborations with local and international institutions to pioneer research and development (R&D) and new water management techniques. It featured WaterWiSe, a real-time water quality and distribution monitoring system developed in collaboration with the infrastructure-management company Visenti, which is improving the operational efficiency of Singapore’s water supply system. Similarly, this issue’s “Feature” highlights the development of aquaporin-based biomimetic membranes for water re-use and desalination and is an excellent illustration of the issue’s theme—how Singapore is leveraging on R&D to allow us to meet our water needs until 2060 and achieve long-term water sustainability.

The “People in Water Research” series continued in Issue Four with Dr Joan B. Rose, chairperson of the PUB External Audit Panel, who reflected on her experiences as part of Singapore’s water research community with its extensive water infrastructure and scientific expertise. In this issue, the first Lee Kuan Yew Water Prize laureate, Dr Andrew Benedek, discusses the prize and how it served as an impetus for him to crystallize his plans for achieving water sustainability. Additionally, “Facilities Focus” looks at how PUB is utilizing R&D in the creation and management of Singapore’s total water catchment and reservoir system—an essential element of the nation’s water resources.

PUB continues to stay committed to seeking and developing relationships with companies that work in water and water-related fields. The total number of R&D project partnerships in which PUB has engaged currently stands at 410, and they are collectively valued at over S$340.8 million. The healthy increase in partnerships means that we can continue to expect promising innovations from such collaborations in the future.

In the “Research Highlights” section, we present some of the latest R&D from PUB-affiliated laboratories and companies, including projects currently being test-bedded at PUB facilities. The research showcased here provides just a snapshot of our ongoing efforts to ensure a water supply that is adequate, efficient and sustainable for the Singapore of today and of the future. We hope that you enjoy learning about some of our recent activities, and encourage those with water R&D ideas to collaborate with us to help achieve a more sustainable future.

**Chew Men Leong**  
Chief Executive, PUB, Singapore’s national water agency  
Executive Director, Environment & Water Industry Programme Office
Harnessing innovation: A sustainable water supply for a thriving future

From sourcing water to turning used water into pure drinking water, Singapore is home to some of the most advanced initiatives across the entire water supply process. The country’s water management strategies aim to secure a sustainable supply to meet the growing demand of its population and industries. Taking the lead role in the management of water resources is PUB, Singapore’s national water agency. Together with other government agencies and partners in the water industry and academic institutions, PUB’s research and development activities stimulate new ideas and technology, positioning Singapore as a global hub for water resource research and management strategies.

With its lack of natural resources, Singapore taps into innovative water technologies to meet its domestic and industrial water requirements. The current demand for water stands at about 400 million gallons each day—enough to fill more than 6,000 Olympic-sized swimming pools. By 2060, this figure is expected to almost double. Long-term water security is, therefore, unquestionably vital for Singapore’s future.

Meeting today and tomorrow’s demands
To ensure that Singapore can continue to meet its water needs, the government has established a targeted research and development (R&D) programme and adopted new technologies to produce and treat water efficiently. NEWater is one of the products of this programme. First introduced in 2003, NEWater is produced by further purifying treated used water with advanced membrane technologies. It is ultra-clean and safe to drink, having passed more than 100,000 scientific tests, and exceeds the World Health Organization (WHO)’s drinking water quality standards.

NEWater can currently meet 30% of the nation’s water needs and Singapore aims to expand this capacity to meet up to 55% of future demand by 2060. To achieve this goal, the country’s used water system must keep pace with Singapore’s continuing growth. The Deep Tunnel Sewerage System was conceived as a long-term solution for used water management in Singapore. Used water from northern and eastern Singapore is transported entirely by gravity through a deep tunnel sewer to a centralized water reclamation plant for treatment. The treated used water is then discharged into the sea or further purified into NEWater at the NEWater plants. Phase one of the project was completed in 2008, while the second phase, which covers the western part of Singapore, is currently at the planning stage and is slated for completion in 2022.

However, NEWater is just one of the ways in which Singapore is ensuring a sustainable supply of water for its people. Desalination, for instance, offers another viable source of water. In September 2005, Singapore opened its first desalination plant, which
produces 30 million gallons of water daily. In September 2013, a second, larger, S$1.05 billion desalination plant commenced operation, producing a further 70 million gallons of water daily.

PUB is also expanding its water catchment area to further augment the sustainability of Singapore’s water supply. Since 2011, Singapore’s catchment area has increased from half to two-thirds of its land surface area through the completion of the Marina, Punggol and Serangoon reservoirs—bringing the total number of reservoirs across the island to 17. In the long term, Singapore aims to convert up to 90% of its land area into water catchment by targeting the brackish streams and small rivers that flow near its shoreline. To render this water usable, PUB has developed a dual-function variable salinity plant that can treat rainwater during the wet season and then switch to seawater desalination during the drier months.

Partnerships in water research
Water from local catchments, imported water, NEWater and desalinated water make up Singapore’s comprehensive water supply strategy known as the Four National Taps. This strategy, and the way in which it has developed Singapore’s strengths in integrated water management, has raised the nation’s profile as an important developer of sustainable water solutions and drawn considerable interest from the water industry and governments around the world.

Singapore is now home to a vibrant water research landscape engaging 130 companies and 26 research institutions. The country’s National Research Foundation has committed S$470 million to promote and develop water technology R&D since 2006. PUB’s core areas of focus—Intelligent Watershed Management, Membrane Technology, Network Management, Used Water Treatment, Water Treatment and Water Quality and Security—ensure that fundamental research into a wide range of water issues can be efficiently translated into applied technologies.

Water-related R&D efforts in Singapore are led by PUB through the Environment & Water Industry Programme Office (EWI). The EWI is an inter-agency body that includes the Economic Development Board, International Enterprise Singapore, the enterprise development agency SPRING Singapore, as well as academic partners including Nanyang Technological University, the National University of Singapore and the Agency for Science, Technology and Research, and is spearheading efforts to transform Singapore into a global hydrohub.

PUB owns and manages extensive water storage and treatment facilities. To facilitate innovation, PUB has made its water infrastructure—including waterworks, reclamation plants, NEWater plants, reservoirs and stormwater canals—available to both public and private sector organizations for the testing of new technologies. More than 40 projects have been approved over the past 3 years. The on-site testing offers technology developers the chance to conduct trials under real operating conditions, and PUB the opportunity to tap innovative proven technologies to uphold its mission of ensuring an efficient and sustainable water supply.

The R&D partnerships coordinated by PUB have shown that collaborations not only reduce costs and risks for the partners; they also often result in technological innovations. The development of novel biomimetic membranes that could pave the way for low-energy desalination—the focus of this issue’s “Feature” article—is one such notable success.

Appreciation for water
While safeguarding Singapore’s water supply is a vital part of PUB’s remit, the agency also works to mediate demand by educating residents and industry about judicious water use. Since 2003, PUB has run water conservation programmes such as the 10% Challenge and the 10-Litre Challenge, which encourage industry to cut 10% of their consumption or residents to reduce their daily water usage by 10 litres, respectively. PUB also assists residents’ committees to form Water Volunteer Groups that conduct house visits to teach homeowners about water conservation and install water-saving devices. These wide-ranging water conservation strategies have brought Singapore’s per capita daily domestic water consumption down from 165 litres to the current 152 litres—a significant push towards PUB’s target of 140 litres by 2030.

Although a necessity, water can also be a source of leisure and relaxation. With this in mind, PUB is inspiring city dwellers to keep their waterways clean and to conserve water through its Active, Beautiful, Clean Waters (ABC Waters) programme. Transforming drains, canals and reservoirs into visually appealing and clean streams, rivers and lakes that are integrated with parks and green spaces, the ABC Waters programme is successfully bringing people closer to water, allowing them to appreciate and cherish this precious resource.

Wide-reaching impact on water management
The water expertise accumulated through Singapore’s water R&D, education and conservation programmes has transformed the country into a global leader in water management and technology. Undoubtedly, Singapore’s forward-thinking investment in building a sustainable water supply has helped to position the nation as a global hydrohub. Continued efforts will ensure that the impact of Singapore’s contributions to the water industry is felt far beyond its shores.
Looking to nature for sustainable desalination

Desalinated water is one of Singapore’s sources of water. However, given the large amounts of energy required for the process, the cost of treating seawater for potable use is an increasing concern and prompts the urgent need for innovative low-energy approaches. PUB, Singapore’s national water agency, is supporting research to develop artificial membranes containing aquaporins—proteins that conduct water molecules through biological cells while filtering out solutes. This new and innovative technology could potentially strengthen the viability of desalinated water as an affordable and sustainable source for the future.
Research and development (R&D) effort is the key through which Singapore aims to turn its vulnerability—a lack of natural water resources—into a strength and ensure a sustainable water supply that can meet the growing demand of its people and industries.

PUB promotes the country’s water R&D efforts through the Environment & Water Industry Programme Office (EWI). It has developed plans for enhancing water security and sustainability through increasingly more efficient water management practices, including the formulation and implementation of new water-related policies and significant investments in infrastructure and technology.

Desalination as one of the Four National Taps
Desalination is an obvious choice for a nation surrounded by seawater such as Singapore. In 2005, Singapore’s first desalination plant opened and it has since provided a reliable source of water for the population. Desalinated water, together with local water catchments, imported water and high-grade reclaimed water known as NEWater, make up Singapore’s Four National Taps—the nation’s diversified and sustainable solution to its water needs.

As Singapore’s economy and population continue to expand, its demand for water will also increase, making the long-term security of water supply of utmost importance. To this end, PUB has plans to ensure that the nation’s future water needs will continue to be met. In the long-term, 90% of Singapore’s land area will become water catchment, while NEWater and desalinated water is expected to meet up to 80% of the country’s total water needs by 2060.

Challenges of desalination
Like Singapore, a growing number of other countries are turning to desalination to bolster water supplies. However, the wider application of desalination as a source of water is constrained by financial, environmental and regulatory issues—a dilemma shared by many nations. While desalination costs have steadily decreased in recent decades, further significant reductions may not be possible with existing technologies.

Today, reverse osmosis is the most commonly employed desalination technology. The process involves forcing seawater across a water-permeable membrane that prevents dissolved salts and minerals from getting through, resulting in pure drinking water. Substantial energy is required to power the pumps that produce the pressure required to push seawater through these membranes. Thus, electricity expenses make up almost half of the operating costs for desalination. The high energy requirement of the process also raises concerns about associated greenhouse gas emissions and its relevance as a climate change adaptation measure.

Planning parameters indicate that by 2060, the total energy requirement for desalination will be five times greater than at present if Singapore continues to use current reverse osmosis technology. Therefore, more energy-efficient solutions—particularly in the area of membrane innovation—are needed to ensure that desalination remains a viable source of water for Singapore.

Nature knows best
For millions of years, organisms living in high-salinity environments have been exploiting seawater for their survival, using negligible amounts of energy. This process is facilitated by water channel proteins known as aquaporins. Described as the ‘plumbing system’ of the cell, aquaporins have narrow pores that prevent large molecules and salts from entering the cell while maintaining an extremely high water permeation rate (Figure 1).

Conceptually, artificial membranes may be developed to mimic these biological processes by incorporating aquaporins into an ultrathin layer of an organic material, such as lipids. These aquaporin-based biomimetic membranes can potentially be used in reverse osmosis, paving the way for lower-energy desalination. However, the synthesis of such membranes is a challenge. Aquaporins are difficult to produce in large quantities due to their complex structure and hydrophobic nature. The aquaporin-based biomimetic membranes that have been produced so far are too small and fragile to withstand the high hydraulic pressures used in industrial water purification processes.

Strategic partnership for membrane innovation
In response to the EWI’s call for proposals in water technology, the Singapore Membrane Technology Centre (SMTC) at Nanyang Technological University (NTU) in Singapore, Danish company Aquaporin A/S and international consulting firm DHI Water & Environment forged a partnership in 2008. Their ambitious project to create durable, high-permeability aquaporin-based biomimetic membranes for water re-use and desalination received $3 million in funding from Singapore’s National Research
Foundation under its Environmental and Water Technologies Strategic Programme.

The three collaborators each brought different skills to the project. The SMTC was responsible for the overall planning of the project, including membrane design, synthesis and optimization. Aquaporin A/S provided experience and initial protocols for combining aquaporins with other materials as well as independent testing of the membranes developed. The Singaporean arm of DHI Water & Environment, an independent consulting and research organization in the fields of water, environment and health, took charge of computational simulation studies.

Several other academic partners also participated in the effort. Aquaporin preparation and purification and molecular dynamics simulations were performed at the NTU School of Biological Sciences, and the NTU School of Materials Science and Engineering participated in polymer-aquaporin studies.

A new membrane is born
The interdisciplinary team successfully developed a new method of creating robust, high-permeability aquaporin-based biomimetic membranes. Through interfacial polymerization—a process involving the interaction of two solutions at the atomic level—a thin-film composite of aquaporin-based biomimetic membrane was synthesized. What makes this method unique is that during the fabrication process, bubble-like structures—known as vesicles—loaded with aquaporins were added to the membrane surface through a cyclic process, strengthening the permeability capabilities and integrity of the resulting membrane (Figure 2).

To date, the researchers have fabricated membranes of more than 200 square centimetres in size (Figure 3) compared to the efforts of other laboratories, which have only managed to produce biomimetic membranes a few square centimetres in size. When tested against existing commercial reverse osmosis membranes, early prototypes of the new membranes exhibited approximately 40% higher water permeability. The team has now created membranes with double the water permeability of the initial prototypes by optimizing the aquaporin loading. The inherently delicate nature of aquaporin-based biomimetic membranes has also been overcome with the new design because the cross-linked structure of the vesicles contributes to a supporting scaffold.

This is the first time a durable aquaporin-based biomimetic membrane has been manufactured using the interfacial polymerization method. The team’s fabrication process can be easily scaled up to achieve membrane sizes of several square metres or more—large enough to be deployed in actual desalination processes. The novel membranes will be commercialized through Aquaporin Asia, a Singapore-based joint venture between the partners.

Lower-energy desalination within reach
A new project—jointly funded by PUB and the SMTC—commenced in August 2013 to validate and test the membranes over longer periods of time outside of the laboratory and with synthetic used water, as well as effluents from real used water plants and coastal seawater. If proven successful, the biomimetic membranes could also be used in the production of NEWater at lower pressures and hence reduced energy cost.

Although the application of aquaporin-based biomimetic desalination membranes is yet to be realized commercially, the promising results achieved by the researchers suggest that lower-energy, lower-cost desalination may well be a reality in the near future. This home-grown innovation brings benefits not just to Singapore but also to the international community by solving one of the world’s most pressing problems: providing clean water for all at an affordable cost.
Membranes for water re-use
I have long believed that in a world of increasing population, water re-use will become an absolute necessity. The membrane company I founded, ZENON Environmental, focussed on developing low-pressure immersed membranes for water re-use. At that time, some cities in the United States were interested in water re-use, but the potential projects were moving very slowly.
However, half the world away, the government of Singapore announced a strategic move towards water re-use on a nationwide scale. As soon as I read about the ambitious programme, my mind was made up: our company would have to do whatever it took to become a supplier to the NEWater water reclamation projects, so as to gain credibility in water re-use. In 1999, we opened ZENON’s office in Singapore and were soon fortunate to be chosen as a membrane supplier for the Bedok Water Reclamation Plant and subsequent other projects.

Water pioneers
Singapore became the hub of our Asia offices. I started to visit the country regularly and had the pleasure of getting to know many of the NEWater pioneers including Tan Gee Paw, Harry Seah and Ong Choon Nam. My admiration for them and the way in which the Singapore government approaches water issues started a love affair with Singapore that continues to this very day. The pace and quality of the water re-use programme amazed all of the water professionals I knew, and NEWater has since become a beacon for the world in water re-use.

The Lee Kuan Yew Water Prize
In 2008, the Singapore government, with the leadership of PUB, Singapore’s national water agency, launched Singapore International Water Week and created the prestigious Lee Kuan Yew Water Prize, whose recipient delivers an eponymous lecture to a large audience during the conference. I was astonished at how fast Singapore International Water Week became an essential conference for the water industry to attend. However, the biggest shock of all came when Khoo Teng Chye informed me that I had been selected as the inaugural winner of the prize.

Deeply honoured, I felt an obligation to do the award justice and decided to use the lecture to not only describe what had happened in the past, but also to share and discuss with the audience what needs to be done in the future to improve water management. A key area I chose to highlight was the assertion that the used water treatment plants of the future should be ‘energy positive’.
I pointed out that—with judicious use of existing technologies—the organic waste that enters used water treatment facilities is capable of providing enough energy to power most such plants. Furthermore, twentieth-century efforts to treat used water had been largely directed at meeting water quality objectives and the energy cost had not been an important consideration. I proposed that we focus more of our attention on improving anaerobic digestion, as the principal way of removing organic material from water in treatment plants.

The water–energy nexus
After the conference, I became committed to the idea of developing anaerobic digestion as a water treatment technology. Although already being adopted in warm-climate countries such as Brazil, much more research would be needed to ensure that the process could meet the stringent water quality requirements of developed countries.

With these goals in mind, I started an anaerobic digestion company—now known as Anaergia. The company is focussed on creating reusable water, energy and fertilizer from used water, thereby lowering the cost of treatment and making the process sustainable. Anaergia also exploits anaerobic processes to treat organic waste on its own or to co-digest it with used water sludge.

Back in 2008, when I received the Lee Kuan Yew Water Prize, this was just an idea. Today, Anaergia is a global company and I am very excited by the fact that the technologies developed have the capability to accomplish my original dream. And the location of Anaergia’s head office in Asia is, of course, Singapore.
Singapore’s reservoirs for tomorrow

MacRitchie Reservoir, one of Singapore’s 17 reservoirs
In Singapore, 17 reservoirs and a vast network of waterways comprising 8,000 kilometres of rivers, canals and drains form an essential part of the nation’s goal to ensure an adequate, robust and sustainable water supply for generations to come.

Although just a small densely populated island, Singapore is one of the few countries in the world to harvest urban stormwater on a large scale for its water supply. Reservoirs make a key contribution to Singapore’s first National Tap by collecting and storing the country’s rainwater—known as local catchment water. In addition, Singapore’s reservoirs provide the community with popular venues for recreational activities and offer excellent opportunities for test-bedding projects to advance innovative research.

Marina Reservoir—Singapore’s first reservoir in the heart of the city

At iconic Marina Reservoir, water management encompasses an array of projects designed to promote sustainability, efficient use and optimization of freshwater resources.

Managed by PUB, Singapore’s national water agency, Marina Reservoir has a catchment area of 10,000 hectares—the largest among the nation’s reservoirs—and is the first to be located in the heart of Singapore’s vibrant city centre (Figure 1). The reservoir is capable of meeting 10% of the nation’s water needs and, together with Punggol Reservoir and Serangoon Reservoir, raises the proportion of Singapore’s land surface used for water catchment from half to two-thirds—a significant boost for the country.

The Marina Reservoir and Barrage project was originally conceived in the late 1980s by former Prime Minister Lee Kuan Yew, who recognized the value of building a low-level dam across the mouth of the Marina Channel. When current Prime Minister Lee Hsien Loong officially opened Marina Reservoir and Barrage on 31 October 2008, the S$226 million project was widely hailed as a feat of engineering due to its sheer scale and logistical complexity. The Marina Barrage has won international acclaim for its innovative design and received the highest honour at the American Academy of Environmental Engineers (AAEE) Awards in 2009 in recognition of these accomplishments.

Researchers at PUB are now collaborating with both private and public sectors using Marina Reservoir as a case study to accomplish the synergistic goals of improving early warning capabilities and forecasting systems, enhancing flood control measures and integrating atmospheric, rainfall-runoff, reservoir and coastal hydrodynamics.

Leading research into reservoir management

In order to manage Singapore’s total water catchment and reservoir system, PUB must gather as much information as possible about the amount and quality of water flowing into reservoirs before the water is treated for potable use. “It is because of this need that PUB decided to participate in and co-fund the Multi-Objective Multiple Reservoir Management research programme, which has four work packages that look at different aspects of our catchment and reservoir management,” explains Tan Kok Meng, a senior engineer and project member at PUB.

The main objectives of the work packages comprise: integrating control of reservoir operation techniques; improving rainfall forecasting models; calibrating rainfall-runoff processes; and developing meta-models for reservoir water quality. PUB reservoirs and catchments serve as important test cases for this collaborative programme run jointly by PUB, the National University of Singapore (NUS), independent research institute Deltares and the Tropical Marine Science Institute of NUS. The programme has led to the development of new methods for the emulation and control of salinity in Marina Reservoir.

Optimizing reservoir operation

PUB researchers optimized a new reservoir management routine based on a system known as Dynamic Emulation Modelling (DEMo), which has the advantage of producing faster computational outputs than other models currently in use. In addition, “the emulator developed for water movement and salinity could be further extended to other water quality parameters to take advantage of the fast computation time,” says Tan.

Besides salinity, other useful parameters such as chlorophyll a and dissolved oxygen concentrations as well as the total amount of suspended solids may be investigated in the future. Marina Reservoir experiences algal blooms and fluctuating conditions due to its urban surroundings; implementing a model-based approach.
Facilities Focus | Singapore’s reservoirs for tomorrow

optimization routine that builds on the DEMo study could therefore provide a highly effective way to support the real-time operation of the Marina Barrage.

Forecasting rainfall
In a country where annual rainfall exceeds 2,400 millimetres and daily rainfall can reach more than 200 millimetres, the likelihood of flooding is elevated. In order to enhance Singapore’s capability in managing flash floods and implementing early warning systems, it is essential to develop accurate models for rainfall forecasting.

In response, PUB scientists and collaborators have been investigating new approaches to rainfall forecasting and ‘nowcasting’—the prediction of high-impact weather events over shorter timeframes—using satellite imaging systems (Figure 2).

By combining a numerical weather prediction model created for 24-hour rainfall forecasting with a radar-based model that yields accurate nowcasting estimates covering 3-hour timeframes, the research team was able to develop an integrated system known as the Ensemble Rainfall Forecast System. This model has been incorporated into PUB’s operational management strategy and enables faster, improved estimates of rainfall, so as to provide better flood management.

Improving drainage systems by studying rainfall runoff
Rainfall-runoff modelling offers a powerful tool for studying flood control. In turn, the data acquired from rainfall-runoff models can be usefully applied to improve drainage engineering systems. For this reason, researchers at PUB, Deltares and NUS have been undertaking a detailed analysis of rainfall-runoff processes at an 8.5-hectare catchment located at the NUS Kent Ridge campus in southwestern Singapore.

The studies involve measuring flow rates and water levels in drains through a flow monitoring programme, as well as gathering data about infiltration rates in relation to urban soil, in order to determine rainfall excess and deepen understanding of rainfall-runoff relationships.

Understanding stormwater quality
To develop a better understanding of stormwater runoff and its meteorological and flow characteristics, PUB has been carrying out extensive research at Kranji Reservoir in northwestern Singapore through a project that began in 2007. Jointly funded by PUB and the School of Civil and Environmental Engineering at Nanyang Technological University, the Kranji catchment study offers valuable insight not only into the Kranji watershed but also other areas in Singapore with comparable types of land use.

The Kranji catchment area is unique in having one of the most diverse types of land use in Singapore, ranging from forests and farmland to areas used for residential and military purposes. As part of the study, the Kranji catchment area was divided into sub-catchment zones that were monitored to gain an understanding of stormwater quality and runoff under particular land uses (Figure 3). By applying a data-driven approach to improving the modelling of catchment flow and water quality, the Kranji catchment study aims to develop an integrated water quality model with real-time predictive capabilities.

Water quality through innovation
Advanced technology has enabled PUB to better monitor water quality, such as through the collection of real-time data to support operational and management decisions, and the development of bio-indicators to monitor long-term changes. Innovations in pollutant control measures, such as constructed wetlands, and enhanced bioengineering methods for nutrient removal, further complement PUB’s watershed management strategies.

By undertaking a wide range of collaborations and encouraging test-bedding projects, PUB is committed to promoting best practices in reservoir management and applying innovative solutions to environmental challenges. For more information, please visit pubwaterresearch.com.sg.

Fig. 2: Rainfall and flood monitoring are made possible by satellite imaging systems

Fig. 3: Map of the Kranji Reservoir catchment and local water quality monitoring stations
Intelligent Watershed Management

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

Microbes that can cause algal blooms in Singapore’s reservoirs are now detectable remotely in hours instead of days

Researchers in Singapore have developed a system for almost real-time and remote detection of microbes that can cause algal blooms. Combined with predictive modelling tools, this early warning technology will enable decision makers to anticipate the onset of a bloom and mitigate any associated health threats. The technology will also contribute to ensuring the long-term safety and sustainability of Singapore’s water supply.

Most microbes are non-hazardous and essential for ecosystem functioning, but some can produce blooms that pollute drinking water sources or contaminate seafood. Current detection methods require transporting water samples to a laboratory for analysis, which may delay results until it is too late to take precautions.

In close collaboration with PUB Singapore, a research team at DHI Water & Environment and the Advanced Environmental Biotechnology Centre of Singapore’s Nanyang Technological University, led by Ole Larsen and Aurore Trottet, developed the early warning system. The system employs an environmental sample processor (ESP), a portable water laboratory that can be deployed in or near a test site (Fig. 1). The ESP collects water samples, analyses them for harmful microbes and transmits results via the internet or mobile phone network. Current monitoring methods take up to 48 hours to produce results, whereas the ESP takes less than 4 hours.

Early preventive action is vital in effectively managing algal blooms. “Our early detection system will allow PUB to redirect or secure water sources, or adjust treatment protocols,” explains Larsen.

The ESP identifies suspect microbes by matching their DNA or protein signatures with a library of samples from known microbes. The system is highly accurate and can detect low levels of specific organisms. To prepare the ESP for deployment in Singapore’s waters, the team conducted a year-long study at Pandan Reservoir and the western Straits of Johor. They identified a number of microbes (Fig. 2), including the toxin-secreting cyanobacterium *Microcystis* sp., which requires a higher degree of raw water treatment to remove it and raises the cost of water production.

The ESP technology will also contribute to the currently limited understanding of microbial ecology, Larsen notes. This technology can be deployed for as long as three months and takes sequential samples. The results of this long-term, frequent sampling can be combined with other environmental data to build more accurate models for environmental forecasting.

“Understanding the factors controlling algal blooms is very important,” says Larsen. “The data obtained from the ESP will enable near real-time prediction of water quality, which will enhance our understanding of the seasonal turnover of microbial ecology in the ecosystem.”

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Fig. 1: The environmental sample processor (ESP) uses molecular probes to identify microorganisms that could cause an algal bloom

Fig. 2: The ESP contains molecular probes that can detect cyanobacteria species during real-time monitoring of Singapore’s reservoirs
A non-toxic approach to algae control

Technology that boosts oxygen levels in stagnation-prone waterways enables chemical-free control of bacterial communities

Sungei Peng Siang is a primary tributary of Singapore’s Kranji Reservoir and provides a scenic backdrop for the Warren Golf & Country Club (Fig. 1). During the hot season, the waterway tends to stagnate and form algal blooms. These algae deplete available oxygen and allow anaerobic bacteria to flourish, creating an uncomfortable environment for visitors.

“The odorous stench emitted from these algal blooms was causing an unpleasant and irritating nuisance,” says Andrew Kwa, sales manager for Singapore-based SIF Technologies.

To avert algal bloom formation, SIF has developed a promising technological solution, known as dpasys\(^*\), which stands for ‘DisPersion Algorithm System’. PUB Singapore recently facilitated the company’s testing of the technology in a pilot project at Sungei Peng Siang.

To test this approach, SIF scientists collected water each fortnight at four different sites in Sungei Peng Siang from February 2012 to January 2013. In early October 2012, dpasys units were brought online (Fig. 2). After comparing critical water quality parameters pre- and post-treatment, the researchers determined that the system was performing effectively.

“The dpasys technology has the ability to actively produce and maintain dissolved oxygen in open water and also reduces the variation in dissolved oxygen levels,” says Kwa. Furthermore, there were no complaints about the river’s odour throughout the duration of this pilot project.

PUB and SIF have continued to monitor water quality at this site through the remainder of the hot season. They are aiming to identify additional performance gains and to determine whether this technology might prove useful in combating similar algal blooms elsewhere in Singapore. Accordingly, Kwa reports that SIF’s top priority is to make the technology portable. SIF is in discussion with PUB on the possibility of deploying its technology to service affected and susceptible areas.

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**Fig. 1:** In the past, the tributary of Sungei Peng Siang has experienced the accumulation of algae and bacteria during the hot season.

**Fig. 2:** A three-month trial of the dpasys technology showed that the chemical-free ‘hydrocavitation-based’ system increased water movement and dissolved oxygen levels in the waterway.

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PUB Singapore adopts a holistic ‘source–pathway–receptor’ approach to flood protection in Singapore and continually reviews its public drainage system, enabling it to cope with increased weather uncertainty as well as rising urbanization (Fig. 1).

To further improve the understanding and management of flooding in the drainage network, PUB recognises that new data and models are required to better analyse, model and predict flash floods.

To this end, Albert Goedbloed, Joost Buurman and colleagues at the National University of Singapore, in collaboration with the Dutch research institute Deltares, are developing cutting-edge software for PUB’s Operational Management System (OMS). The work is particularly focused on the Stamford Canal subcatchment of the Marina Reservoir catchment area.

After a flood in this catchment in 2010, PUB raised a section of the Orchard Road shopping boulevard and made plans to build a diversion canal and detention tank in the Stamford Canal subcatchment. “This meant that the initial models that were developed and incorporated into the OMS required modification and calibration,” explains Goedbloed. “A natural follow-up is to enhance the early warning capabilities within the OMS, with a specific focus on the Stamford Canal subcatchment.”

The team is implementing a new modelling software called 3Di, developed by a research consortium in the Netherlands, of which Deltares is part. The software exploits detailed digital elevation models (Fig. 2) acquired through laser scanning to determine the exact path of floodwaters.

According to Goedbloed, the information from 3Di will provide PUB with an indication of which areas to monitor during extreme storm events. “The model could also be used to test the effectiveness of mitigation measures before they are implemented,” he says.

Although the 3Di model greatly improves drainage modelling, flood forecasting still depends on accurate rainfall prediction. Such forecasts are notoriously difficult for a tropical climate, but the researchers are working on a solution. As Goedbloed explains: “We aim to improve the lead time of the rainfall prediction, leaving more time to implement mitigation measures and protect property in the specific areas where flooding is expected.”

The project will run until the end of 2013, and the researchers are optimistic that their software will help PUB to enhance the management of Singapore’s drainage network.

“Apart from the recent localized flood events across the island, the drainage system in Singapore functions very well,” says Goedbloed. “Measures have been put in place or are under development, like our project, to make sure that we can deal with any future flash flood event.”

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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 and used water treatment.
Power generation from used water

Durable, semipermeable membranes generate renewable energy by tapping the power of osmosis

Tai-Shung (Neal) Chung and his team at the National University of Singapore have developed a membrane that can withstand high pressures and generate an economical power output.

When seawater and freshwater are separated by a semipermeable membrane, the freshwater flows through the membrane and dilutes the saltier side. However, in a variation of this process known as pressure-retarded osmosis (PRO), the high-salinity water is under pressure. As water flows through the membrane it raises this pressure further—enough to drive a turbine to generate electricity.

Norwegian energy company Statkraft has calculated that each square metre of membrane must be able to generate more than 5 watts of power for the process to be commercially viable. Current membranes, however, can not meet this power density—often because they do not allow enough water to pass through. They also tend to deteriorate quickly under the high-pressure conditions required.

The membrane developed by Chung and colleagues is a thin-layer composite roughly 50 micrometres thick, formed by coating a membrane support made from the polyimide polymer Matrimid with a polyamide.

Performance tests showed that the PRO membrane could withstand pressure some 15 times greater than atmospheric pressure and generate up to 12 watts of power per square metre. The team has recently boosted this performance by forming the membrane into hollow fibres.

“We believe that the hollow-fibre membranes have great potential for osmotic power harvesting,” says Chung.

Chung’s group has also investigated dual-layer hollow-fibre membranes based on polybenzimidazole (Fig. 1). This polymer forms durable semipermeable membranes but they tend to be brittle, thus limiting its large-scale application. As a workaround, the researchers added nanoparticles made from clusters of silsesquioxane molecules, which have a cage-like structure composed of silicon and oxygen atoms. These nanoparticles strengthen the membrane and allow more water to pass through it. In combination with a second polymer used as a supporting layer, this hollow-fibre composite membrane could generate about 2.5 watts of power per square metre at 7 times the atmospheric pressure. The team is now working to further improve this performance.

Chung says that if PUB Singapore develops an osmotic power system, its feedstock could include residual water from used water reclamation, as well as the concentrated saline waste from the reverse osmosis process that produces freshwater for the island (Fig. 2). Not only would this generate energy, he says, but it would also help to alleviate an environmental waste disposal problem and make desalination more sustainable.

This research is funded by the National Research Foundation through the Environment & Water Industry Programme Office.

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Membrane Technology | Research Highlights

Understanding what makes biofoulants stick

Insight into how biofilms form points the way to cleaner and more efficient water production and treatment in Singapore

Fig. 1: Reverse osmosis (RO) filters in desalination and water treatment plants can become clogged and inefficient when coated by biofilms

Fig. 2: Example of a biofilm that hinders water flow through a pipe; biofilms that form on RO membranes impede water flow in a similar way

Fouling of the reverse osmosis (RO) systems used to desalinate water and treat used water in Singapore may soon become a problem of the past. Working in collaboration with PUB Singapore, a team led by Harvey Winters at Singapore’s Nanyang Technological University has identified the likely initiators of unwanted biofilms on RO membranes (Fig. 1).

Omnipresent in seawater and used water, the biomolecular substances called transparent exopolymer particles (TEPs) readily aggregate into sticky, gel-like structures that lead to biofilm formation and hinder water flow (Fig. 2). To better understand the composition and size distribution of TEPs—so that improved treatment measures can be implemented—Winters and his team developed a novel analytical approach.

First, the team considered the sources of TEPs. Winters notes that other studies on TEP-mediated biofouling have focussed on algal secretions and overlooked the likelihood of secondary but important sources of these particles such as zooplankton and bacteria. As a proof of concept, the researchers isolated and characterized TEP-like particles secreted from marine and used water bacteria, as well as algae.

They detected the presence of membrane-fouling proteins and long carbohydrate molecules in the isolated particles. The carbohydrates dominated the algal samples, but high protein concentrations and low-molecular weight compounds, which can produce larger biopolymers and aggregates, dominated the bacterial samples. Agglutination tests revealed that blood cells clustered around both algal and bacterial TEP-like substances, carpeting the bottom of the test tubes. Similar to proteins located on these blood cells, bacterial proteins recognize the receptors of the TEP-like particles, promoting binding interactions between bacteria and particles.

According to Winters, most water scientists believe that nanometre-sized aggregates, called colloidal TEPs, and larger particulates over 400 nanometres in size contribute to biofilm formation. In contrast, he proposes that these particles are essentially removed during the filtration that precedes the RO process. “Humic acid and low molecular weight organics that remain in the pre-treated water [act as TEP precursors] and reassemble into colloidal and particulate TEPs during the desalination process,” he says.

Further tests showed that ultrafiltration membranes retained only the large particles, letting the TEP precursors through, and that the transformation of these precursors relied on physicochemical factors, including flux and ion density.

Winters and his team are continuing this project to enhance clean water production in Singapore. They are investigating the mechanism of particulate and colloidal TEP reassembly on the RO membrane and how to prevent this phenomenon.

This research is funded by the National Research Foundation through the Environment & Water Industry Programme Office.

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Waste heat repurposed for water recovery

A system that uses waste heat for water purification could boost the sustainability of industrial water use.

Power stations are a critical component of a country’s electricity infrastructure and consume a considerable amount of water—a tenth of which is released as waste—in order to meet consumers’ demands.

Aiming to boost sustainability by transforming lost water into a useful resource, Singapore’s Environment & Water Industry Programme Office invited memsys Clearwater, a company with bases in Germany and Singapore, to test a solution that exploits another major industrial waste product. “Our premise is to use waste heat and energy from industry to give back very high-quality distilled water that can be used for their internal needs,” explains Niranjan Sarda, international sales director at memsys. “This will effectively reduce [the industrial sector’s] water footprint.”

Virtually every industrial facility releases heat as a by-product. A power station can lose billions of watt-hours of energy as heat every year in parallel with its heavy water consumption, making it an ideal setting for initial test-bedding of the memsys platform. The system maintains the feed stream under vacuum conditions that lower its boiling point; when thermal waste energy is used to heat the system, the water rapidly evaporates and passes through a novel and patented membrane-based system, yielding purified water that is ready for re-use. “By using a combination of evaporation and condensation cycles, we are able to recycle this waste energy multiple times,” adds Sarda.

The memsys technology was tested at a power station in Singapore for the first of a two-phase project that will span a total of three years (Figs 1 and 2). Phase one entailed short-term testing of system performance at both low and high temperatures and was completed in May 2013. This initial testing was conducted at a limited scale, using an external temperature controller rather than actual waste heat. Nevertheless, the scale was sufficient to demonstrate the system’s potential for delivering high-quality distillate. “Currently, the aim is water re-use,” says Sarda. He explains that the water could be refined to obtain high-quality water suitable for use as boiler feed water or for other industrial purposes.

Phase-two testing will focus on real-world performance, drawing on waste energy from a power plant. This second phase will test the system’s long-term energy efficiency and capacity to resist fouling and scaling from contaminants in the recycled water. “At the end of this project period in 2015, we hope we can offer a commercial solution that industries with waste heat available can easily adopt to reduce their water consumption,” says Sarda.

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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.
Nitrogen pollutants take the easy way out

Tests show that bacteria-based technology efficiently removes nitrogen from used water and has potential for large-scale use

Nitrogen-bearing ammonium ions (NH₄⁺) are persistent pollutants in used water sludge that can promote unwanted algal growth. With increased scrutiny of effluents and strong demand for recycled water, researchers are investigating ways to convert these compounds into free nitrogen gas that bubbles harmlessly back into the atmosphere. In collaboration with PUB Singapore, Yasuhiro Fukuzaki and colleagues from the Meidensha Corporation of Japan and Meiden Singapore have completed a test-bedding project that significantly improves the speed and efficiency of ammonium-rich used water treatment. The team’s success is based on a bacteria-driven technology known as anaerobic ammonium oxidation (anammox).

Anammox is an innovative, two-step, microbial process that removes nitrogen from water (Fig. 1). Initially, ammonia-oxidizing bacteria partially convert ammonium ions into nitrite ions (NO₂⁻). Next, special anammox bacteria—discovered in used water sludge in the early 1990s—combine the remaining ammonium ions with the nitrites and transform them into buoyant nitrogen gas, nitrate ions (NO₃⁻) and water. This technology can decontaminate large volumes of used water at high speed and generates less sludge than other approaches, Fukuzaki notes.

Fukuzaki and colleagues constructed a bench-scale reactor to test the feasibility of introducing anammox treatments to Singapore’s Changi Water Reclamation Plant (WRP). First, the team performed tests on samples of the Changi WRP’s ‘dewatering centrate’—a liquid derived from centrifuged sludge—and found it could support high levels of bacterial activity (Fig. 2). Then, they began trials at the site by running a test line to convey the centrate from the dewatering centrifuges to the anammox biological reactor. Most anammox reactors require pre-treatment to remove organic matter, which competes with bacteria for available oxygen. However, the organic matter content of the Changi WRP’s dewatering centrate was low enough not to require pre-treatment before being processed. The elimination of this step could yield significant cost savings in future anammox pilot plants at the Changi WRP.

Maintenance of trace elements in the biological reactor proved to be critical for long-term ammonium decontamination with bacteria. In particular, Fukuzaki notes that iron supplements were required to maintain the efficiency of both ammonia-oxidizing and anammox bacteria. Once these operational parameters were optimized, over 80% of nitrogen-based pollutants were eliminated from the used water sludge. Other organic pollutants and polymers that were used to help with centrifuging had little impact on the bacteria-based clean-up system.

The promising results from this study have led Fukuzaki and colleagues to propose a full anammox processing system for the Changi WRP. According to Fukuzaki, because of the extraordinary efficiency of the nitrogen-removing bacteria, such a move could be vital to realizing stable and sustainable quality of the effluent feeding into Singapore’s NEWater plants.

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Membrane bioreactor (MBR) technology is used in many water treatment facilities to eliminate biological matter. The technology combines filtration systems with sludge-based suspensions of microbes that degrade organic matter. PUB Singapore recently collaborated with Singapore-based company Glowtec Bio to explore the extent to which they could boost MBR efficiency.

Glowtec Bio’s alternative approach to MBR technology employs a strategy known as ‘granularization’ that promotes the formation of self-aggregating, compact colonies of sludge microorganisms. These dense microbial granules are structured in a way that allows different types of microorganisms to co-exist within them (Fig. 1). As such, the granules provide a superior microbial habitat and the microbes can process biological matter more effectively than traditional systems.

Glowtec Bio has been exploring the capabilities of this granular MBR (GMBR) technology for almost a decade. “We proved that GMBR could offer greater benefit in terms of effluent quality, fouling and so forth during a test-bedding project at the Ulu Pandan Water Reclamation Plant (WRP),” says Ong Tze Guan, managing director of Glowtec Bio. “We then made plans to do a full-scale prototype, culminating in our current setup at the Jurong WRP.”

The GMBR system at the Jurong WRP (Fig. 2) has been running since mid-2012 at a capacity of 200 cubic metres of water per day, giving PUB and Glowtec Bio better insight into the system’s performance. ‘Chemical oxygen demand’ (COD) is a critical metric of water treatment, directly reflecting levels of the kinds of organic matter that the MBR technology is intended to eliminate. The Jurong WRP’s GMBR system yielded consistently low COD levels in its output water, even when tested with used water that differed considerably in quality and contaminant levels.

“Compared with existing systems, our demonstration [plant] at the Jurong WRP showed that our system handles a high loading rate with better quality effluent, less residual sludge production and lower operational cost,” says Ong. Early implementation improved process optimization, allowing Glowtec Bio’s scientists and engineers to determine some of the critical parameters associated with proper granule formation.

Owing to the steady accumulation of non-degraded solid biomass, MBR systems are generally vulnerable to membrane fouling. The improved efficiency of GMBR mitigates this problem, but a further reduction in fouling will be a major objective for Glowtec Bio as it refines the technology. The company is also working on strategies to accelerate the implementation of GMBR systems at future sites. Ong notes that speeding up and simplifying the start-up of the system will also be important when scaling up the technology.

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Microorganism clusters get to work
Specially structured aggregates of microorganisms can accelerate the breakdown of organic matter in used water at water reclamation facilities
PUB Singapore maintains four water reclamation plants that process domestic and industrial used water for re-use or environmentally sound disposal. This treatment is currently achieved through what is known as a conventional activated sludge (CAS) process that is effective but also takes up considerable time and energy. Accordingly, when PUB made plans to expand its industrial used water treatment efforts, the national water agency put out a call for new technologies that might prove more efficient and cost-effective.

Researchers at Japanese companies Kuraray and Nitto Denko have demonstrated a promising alternative approach in a recent pilot project. In the CAS process, aerobic bacteria are recruited to break down solid biological waste present in sludge, after which the resulting water is subjected to additional filtration and processing to remove other undesirable elements.

Kuraray has developed polyvinyl alcohol (PVA) gel beads (Fig. 1) that accelerate this process by providing a stable home for these bacteria. “These beads contain micropores within their inner structure (Fig. 2), which support bacterial colonization,” explains Andy Nguyen, an engineer at Kuraray involved in the pilot study. “This increases the density of useful bacteria in treatment tanks and, as a result, the treatment capacity.”

The researchers found that PVA gel processing can reduce hydraulic retention time (HRT)—a measure of how long used water resides in the system. This increased processing efficiency can also be achieved within a smaller treatment system, reducing the power consumption required.

The Kuraray system performed well in the pilot project, slashing the HRT from more than 21 hours with CAS to less than 12 hours. The system also efficiently eliminated biological material from the treated used water. The resulting water quality was adequate for safe post-treatment disposal, and further processing could render the output suitable for re-use. Future feasibility studies will pair Kuraray’s system with microfiltration technology developed by Nitto Denko in an effort to achieve further gains in water quality, as well as overall efficiency and cost-reduction.

More importantly, the PVA processing approach reduces sludge waste output relative to CAS processing. Kuraray’s system is already being implemented for sludge reduction at a facility on Jurong Island in Singapore, where it has performed well while processing up to 9,000 cubic metres of used water per day.

Although this technology is relatively new, Nguyen believes these early demonstrations bode well for its broader utility in water treatment. “It opens up options for both designing new plants as well as retrofitting of old plants,” says Nguyen.

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**Improved housing for a water-purifying workforce**
Gel beads boost water treatment efficiency by providing a haven for bacteria that process biological waste

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**Fig. 1:** A sample of the polyvinyl alcohol (PVA) beads used as the basis of Kuraray’s water treatment process that achieve reductions in the cost of water treatment

**Fig. 2:** Micropores within the PVA beads provide a stable environment for dense colonies of aerobic bacteria, which improve the speed and efficiency of biological waste removal
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.
A research team at Ngee Ann Polytechnic in Singapore has partnered with PUB Singapore to build and test a prototype of a portable and automated system to detect microscopic invertebrates in water (Fig. 1). The prototype can monitor changes in the abundance and occurrence of these tiny animals. Led by Tai Tong Ho, the team tested the prototype’s hardware and control software in a four-week study at a laboratory.

Currently, the detection of microscopic invertebrates in water is undertaken manually by trained scientists. The process is laborious and can only be completed in a laboratory. Any microscopic invertebrates are identified and counted using a microscope (Fig. 2).

In contrast to this manual process, the prototype portable system can accomplish the same task using machine vision. A single stream of water is pumped through a microchannel while a high-resolution microscope, fitted with a black and white digital camera, records images of the micro-invertebrates in each sample. A computerized image-analysis system then compares the results to benchmarks held in an image library. If necessary, adjustments to the water treatment process can be made and re-checked accordingly. While the concept of the system is simple, the team first had to solve several practical problems.

For instance, the micro-invertebrates of interest can range in size from 50 to 1,000 micrometres. Selection of a suitably sized microchannel is therefore critical. It must be of sufficient diameter to accommodate all sizes, allow an optimum flow rate, and accommodate occasional back-flushing for cleaning and unblocking. After careful testing, the researchers determined the optimal channel size for the application.

Deciding on the image recognition system proved more challenging. In addition to their huge size differences, micro-invertebrates can appear in any orientation and present an enormous variety of features. Ho and colleagues therefore evaluated several established object-recognition algorithms. Then, they developed an algorithm that recognizes several families of micro-invertebrates, targeting an accuracy rate of at least 80%. The algorithm is based on measurements of ratios and transformations of organism features and incorporates learning.

Future work will improve the accuracy of the algorithm, the efficiency of the system and possibly extend the function to monitor more types of micro-invertebrates.

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Although highly effective, the techniques currently used at water treatment plants to detect pathogens can take days to complete. In partnership with PUB Singapore, Ai Qun Liu from Singapore’s Nanyang Technological University has developed a laser technology that cuts this detection time from days to hours. The innovative technology can detect single cells of the waterborne pathogen Cryptosporidium in a 10-litre drinking-water sample.

Liu and colleagues’ technology is based on so-called ‘optofluidic waveguides’ that employ the principles of transformation optics—a novel field of light manipulation. Instead of relying on electricity and magnetism to move light beams, however, the team turned to fluids flowing through hair-thin microchannels carved into glass sheets the size of microchips. They found that varying the speed and consistency of liquids through these microfluidic channels could create laser focussing and interference patterns never seen previously.

When contaminated water flows through these tiny microchannels, parasites, bacteria and other particulates hit the laser light and generate distinct patterns that correlate to a certain cellular shape and refractive index. A high-speed optical sensor then captures this scattering data and the system identifies the presence of Cryptosporidium and other waterborne pathogens within an hour.

By combining the optofluidic phenomenon generated by the laser with the precisely constructed microchip waveguides, the researchers fabricated a sensor, dubbed the ‘Parasitometer’, that is ideal for monitoring treated water (Fig. 1). Trials by the research team revealed that this technology had a remarkable success rate and required no additional chemical reagents, which will reduce water quality monitoring costs.

According to Lei Lei, a member of Liu’s team, the need to assess large volumes of water in short time frames was the team’s biggest challenge when developing the optofluidic sensor. To resolve the constraint imposed by the microchips, the researchers turned to silicon-based preconcentration chips (Fig. 2), a type of nano-filter that slows the passage of charged particles through the microchannel. “Using this chip, target contaminants can be enriched in the water sample up to 10,000 times,” he says.

Liu and colleagues recently received a start-up grant from SPRING Singapore’s Technology Enterprise Commercialisation Scheme to bring this highly sensitive and low-cost technology to market. The team is currently working to overcome practical challenges such as reducing the device’s size and weight. Nevertheless, Liu is certain that these findings can boost the sustainability of Singapore’s water system by improving its overall quality and efficiency, thereby helping to establish Singapore as the global hydrohub of water innovation.

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Fig. 1: The new Parasitometer, similar in size to a carry-on suitcase, can detect harmful contaminants in water samples within an hour

Fig. 2: A preconcentration chip that filters charged particles from large volumes of water is essential to the Parasitometer’s high-speed testing of water samples
An automatic choice for water testing

Machine-driven syringe manipulations provide high-accuracy pesticide detection with minimal human intervention

Water treatment facilities need precise analytical devices to detect contaminants such as agricultural pesticides. Often, the tool of choice is gas chromatography/mass spectrometry (GC/MS)—a technique that individually separates chemicals and then measures their molecular weights. However, conventional GC/MS for water contaminant analyses requires cumbersome pre-treatments and large volumes of organic solvents to produce clean extracts containing the contaminants of interest. Now, thanks to a grant administered by PUB Singapore, Hian Kee Lee from the National University of Singapore has developed a rapid and automated pre-treatment-GC/MS technology that can automatically detect trace pesticide residues in water with minimal use of solvent and labour.

Lee’s approach, known as liquid-phase microextraction, uses hypodermic syringes prefilled with solvent to withdraw small volumes of contaminated water samples (Fig. 1) and then expels them. A commercially available autosampler connected to the GC/MS pushes and pulls the microsyringe plunger back and forth to perform this operation (Fig. 2). After several cycles of plunger movements, the organic solvent becomes enriched with the contaminants, which the autosampler then introduces into the GC/MS system.

The efficiency of liquid-phase microextraction inspired Lee and his team to develop an improved version for automated, high-throughput applications. They chose carbamate pesticides—chemicals commonly used to control insects—as a target to demonstrate the feasibility of their water-testing system. Carbamates are difficult to detect by GC/MS; to become traceable, they require an extra processing step known as chemical derivatization, which transforms them into new compounds more amenable for gas-chromatographic analysis. To perform this reaction, the team developed a new in-syringe derivatization process that automatically adds a chemical agent to the microsyringe once the carbamate extraction completes.

Microextraction conducted in this way depends on multiple factors related to plunger movements and solvent properties, so the researchers designed a high-throughput, seamless workflow that generated the best in-syringe parameters for carbamate analysis. Then, they applied these conditions to carbamate-spiked water samples. Their experiments revealed that this automated method had a very low error rate, reliably detecting the pesticides at nanogram per litre thresholds.

Lee notes that the system generates almost no chemical waste, and requires practically no labour. “This system could be installed at a water treatment plant to run multiple experiments for pesticide analysis,” he says. “The operator only needs to initiate the experiment and retrieve the data later for evaluation—everything else is programmed to run automatically.” Lee and his research group are currently developing similar automated technology to detect other water contaminants.

This research is funded by the National Research Foundation through the Environment & Water Industry Programme Office.

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

An integrated approach using a process and membranes specifically tailored for desalination could reduce cost and energy

Meeting Singapore’s increasing demand for pure water is now possible using an energy-efficient and cost-effective treatment of brine, the salty by-product of desalination. A research team led by Anthony Fane and Rong Wang from the Singapore Membrane Technology Centre at Nanyang Technological University developed the heat-driven process in collaboration with PUB Singapore.

Brine represents some 50% of the seawater feed stream and contains twice as much salt as the seawater feed, making further desalting by reverse osmosis challenging. The release of brine into the ocean, or its storage in evaporative ponds, can adversely impact the environment. “Alternate processes that concentrate, and then crystallize brine are capital intensive and require exotic construction materials to stop brine-induced corrosion,” says Fane.

Fane and Wang’s approach combines membrane distillation with crystallization (MDC) and utilizes new process-specific membranes. The MDC process treats brine without requiring secondary disposal. Only the water vapour from the heated seawater feed can pass through the distillation membrane; upon cooling, the vapour condenses into pure water, increasing the ‘recovery’ of the water product. The crystallization unit then converts the remaining brine concentrate into salt crystals.

Owing to a lack of specific energy data, Fane and Wang’s team performed a comprehensive analysis of MDC using process simulations. “These simulations determined the distribution of energy consumption in the system and optimized operating conditions to avoid likely crystal blockage in the membrane distillation module,” they explain. They found that higher inlet temperatures and an additional unit that preheats the brine could enhance energy efficiency.

Next, the researchers manufactured membranes with high porosity to enhance water vapour permeation, and with extreme water-repellence to prevent wetting (Fig. 1). They synthesized the microporous membranes by drawing ultrathin fibres from a poly(vinylidene fluoride) (PVDF) polymer solution. Then, they modified the membranes with a layer of silver nanoparticles followed by hydrophobic organic molecules to tune their surface morphology, roughness and water-repellence.

Performance tests revealed that the new membranes achieved a high and stable water flux with fixed feed and permeate temperatures. These membranes surpassed all other PVDF flat-sheet membranes tested under similar conditions.

Fane, Wang and their colleagues are currently experimenting further with the MDC system (Fig. 2). Moreover, they are exploring different configurations for future scale-up. They are also optimizing the operating conditions to realize a near-zero discharge of brine.

“This research will allow Singapore’s water industry to develop a cutting-edge technology that could provide an innovative solution for the provision of water to industry,” says Wang.

This research is funded by the National Research Foundation through the Environment & Water Industry Programme Office.

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Putting desalination by-products to work

A ‘recycling’ strategy improves the energy efficiency of a method for desalination-by-freezing

Even though they sit in the middle of the ocean, icebergs are composed of salt-free, potable freshwater. This phenomenon occurs because when saltwater reaches a critically low temperature, ice crystals form and grow in a manner that excludes salt molecules. In principle, this same approach could be used in a desalination facility, although the refrigeration process can be prohibitively inefficient in terms of energy use.

Natflow, an energy technology company in Singapore, has been working with PUB Singapore to explore the potential of mitigating these costs by integrating the desalination process with existing climate control systems. “This is possibly the first attempt to combine three services—heating, cooling and desalination—into one process,” explains Tay Cher Seng, managing director of Natflow.

The combined system starts by refrigerating seawater, which yields waste heat as a by-product that can be recovered for use in heating systems. Within the mixture of ice crystals and residual brine, the ice floats to the top and is shaved away by rotary blades and collected in a freshwater tank (Fig. 1). This chilled freshwater is used in cooling systems that drive air conditioning and helps to refrigerate incoming seawater, thus boosting the overall energy efficiency of the system.

“Desalination by freezing is a high-energy process,” says Tay, “but if the energy consumed by the heating and cooling processes is accounted for, the desalinated water could be produced by our system with near-net-zero energy consumption.”

As a pilot project, Natflow tested the system’s capacity to convert seawater into potable water at PUB’s variable salinity plant at Sungei Tampines (Fig. 2). The prototype proved the concept: in the initial run, it desalinated 3,000 litres of water from 30,000 to 3,000 parts per million (ppm) of salt. The refrigeration process provided air conditioning as well as a hot water service sufficient for the equivalent of four hotel rooms.

The team has set a target of reducing the amount of salt in the water to 300 ppm so that it can be considered safe for human consumption. “The separation of the ice from the residual brine is a tricky process,” says Tay. Encouraged by the initial proof of concept for energy-efficient desalination by refrigeration, Tay and his colleagues already have in mind some approaches that might bolster performance in the future. “Going forward, we could add a low-pressure, reverse osmosis system to remove the remaining salt content,” says Tay, although the technology’s core waste heat and chilled water recycling functions are not dependent upon this advance.

This research is funded by the National Research Foundation through the Environment & Water Industry Programme Office.

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A solar-powered desalination system developed and tested in Singapore could improve the availability of freshwater across the island, as well as in remote parts of the developing world.

Seawater has long been purified by distillation, which involves evaporation and then condensation into potable water. Increasingly, however, membranes that separate pure water from seawater are being used for desalination. The most common method is reverse osmosis, which uses pressure to force water molecules through a semipermeable layer and leaves salty water behind.

A technology called membrane distillation combines key features of both techniques. It heats water across one side of the membrane, so that water vapour passes through the pores of a membrane and condenses into a pure liquid on the other side. A research team led by Gurdev Singh of the Environmental & Water Technology Centre of Innovation at Ngee Ann Polytechnic, Singapore, has now developed a more efficient membrane distillation technology called Distil.

This new technology relies on a sandwich of three membranes. The first membrane strongly repels water, which ensures that its pores remain open, allowing water vapour to pass through easily. The second and third layers are progressively more hydrophilic; they attract water molecules and help droplets to condense.

Singh’s team has taken the technology from a bench-scale unit to a solar-powered demonstration plant located at Singapore’s Marina Barrage (Fig. 1). The test-bedding plant contains a series of membrane modules, each packing 1 to 3 square metres of membranes (Fig. 2). Each of the first-generation modules can produce an average of 100 to 270 litres of water during 6 hours of solar irradiance, depending on the membrane area. A further advantage is that no chemical pre-treatment of the water is required.

The demonstration plant at Marina Barrage can remove more than 99% of the salt in the incoming seawater, producing up to 5,000 litres of freshwater per day with a relatively low energy consumption of less than 1.5 kilowatt hours per cubic metre of water.

Singh and his colleagues have also developed a portable unit that can deliver up to 1,000 litres of water per day. This unit could be deployed in remote locations that need drinking water but have no power supply.

The developers are now planning to scale up their Distil system at a larger demonstration plant in Singapore that can use waste heat from industries to produce up to 50,000 litres of high-quality freshwater per day.

This research is funded by Singapore’s Ministry of Education through its Innovation Fund.

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Solar power drives efficient distillation
A triple-layer membrane distillation system cuts the costs of producing freshwater from seawater
Singapore’s water strategy focuses on the management of water resources in an integrated manner across all points of the water loop. In the field of network management, a key aim of water research and development in Singapore is to ensure the delivery of high-quality water from the waterworks to consumers while ensuring the collection and reclamation of used water in an effective and efficient manner.

The management and maintenance of Singapore’s water networks is therefore a critical function, as well as a responsibility that spurs Singapore’s water researchers to even greater technological innovation.
When treated water leaves one of Singapore’s service reservoirs, it flows through a water supply network that contains some 5,400 kilometres of transmission and distribution mains with numerous pipeline branches and loops. The complex network structure makes it challenging to understand the dynamic interconnectivity between water supplied from different service reservoirs (Fig. 1).

Ami Preis at the Singapore-based company Visenti, in collaboration with PUB Singapore, is developing new software to enable PUB’s engineers to divide the city’s pipeline network into detailed sub-zones. This will make it easier to follow water at any point in the system.

“PUB identified a need to better understand the interconnectivity of its water network, which has a very complex topology,” explains Preis. “Our unique software tool will help to simplify the distribution structure by organizing the network ‘endpoints’—the consumers—into clusters.”

The prototype software, which is based on an algorithm developed by Lina Sela at the Massachusetts Institute of Technology, United States, generates a diagram of a selected part of the network, incorporating data such as flow rate and direction through different pipes and valves. It then divides the water consumers into distinct groups, or ‘clusters’, according to how close together they are and which pipelines and valves they share. The software does this by hierarchical structuring, using both bottom-up and top-down methodologies—beginning with a set of individual points and calculating similarities between pairs, or starting with a full network and removing connections between least similar pairs.

“The clustering technique uses a variety of graph algorithms and network search techniques, which can be selected depending on information the user is interested in,” explains Preis. “The result is a connectivity matrix and a tree-like graph, or dendrogram, which represents the interconnections between clusters.”

PUB can then access specific statistical information on each cluster, including demand, consumer population and water flow rates.

More importantly, the software also produces a statistical report on the individual clusters and their interconnectivity, together with a diagram summarizing the hierarchy of the system. Alterations such as new pipelines, pipe closures or diversions can also be added to the network structure within the software, allowing engineers to visualize how the change will alter water flow.

The software will greatly improve understanding, management and control of the water distribution system in Singapore, Preis notes. Better understanding of the water network dynamics will in turn lead to more efficient management of the water system, with significant long-term benefits for the city.

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Quick and efficient dissemination of up-to-date information to the public is a crucial part of PUB Singapore’s role in delivering a healthy and sustainable water supply. The island nation, however, is prone to rapid weather changes during the monsoon season, which can affect its stormwater quality and management.

Realizing the convenience and rapid uptake of smartphone applications, Syed Omar Fadzil and co-workers at PUB recently developed an application, or ‘app’, called MyWaters. The app provides the public with a wide range of services and the latest information about issues such as flood risks (Fig. 1).

PUB, for example, is responsible for managing Singapore’s complex drainage network that must cope with frequent rainstorms. During storms, PUB issues flood alerts and advises on travel conditions. Through MyWaters, users can easily access PUB’s latest information on water levels in key drains and canals (Fig. 2), as well as closed-circuit television images from across the city.

“MyWaters is a utility and lifestyle mobile application available on iTunes, Google Play and Windows Marketplace,” explains Syed. Apart from providing innovative content and notifications on the go, this new app is also designed to encourage the public to take ownership of Singapore’s water resources so that they will protect and use them wisely, he notes.

“The new app also allows users to subscribe to instant notifications from different water-level sensors across the island,” explains Syed. Each subscriber has access to up-to-date information specific to his or her local area. In addition, the app provides tips on how to conserve water, and encourages people to be mindful of their water resources, as well as maintain the cleanliness of the city’s supply.

MyWaters also encourages subscribers to interact with Singapore’s water resources in a fun way through PUB’s Active, Beautiful, Clean Waters (ABC Waters) sites. Current events at these locations across the city, tours of Singapore’s reservoirs and photo-sharing options are all incorporated into the app (Fig. 3), along with water trivia quizzes and links to social media. By engaging with the public in this manner, PUB hopes to promote an understanding of the importance of a sustainable water system for the city.

“We want all members of the public to feel that they are a part of Singapore’s water [story and its] future,” explains Syed. “We will continue to develop the app to provide relevant and timely information to the public, and to engage them in a fun and interactive manner.”

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### Universities, Research Centres and International Organizations

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### Water Utilities and Companies

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