INNOVATION IN WATER Singapore

Volume 10 July 2018

Quenching Our Thirst

A look at the past, present and future of research at PUB, Singapore's National Water Agency

Dragonflies - indicators of good water quality - emerge from a water droplet on the cover of this commemorative issue. With its title penned personally by PUB Chief Executive Ng Joo Hee, "Quenching Our Thirst" looks at how PUB leverages on R&D to ensure that the supply of clean water never runs dry in Singapore. Positive R&D outcomes are driven by pragmatic optimism, reified as energy swirls encircling the droplet. Looking to the future, PUB will continue to embrace advanced technologies and tap on the possibilities offered in the digital space to create safer, more efficient, and more resilient operations to safeguard Singapore's long-term water security.

INNOVAT10N IN WATER Singapore

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

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

Opportunities for collaborative research abound for partners in the water and related industries, universities, and research institutions (local and overseas) who share our objective. You can find out more information about PUB's research and development programme, and how you can begin your partnership with PUB, in the section **R&D at a Glance** or at *www.pub.gov.sg/research*.

Contents

Innovation in Water, Singapore

Innovation in Water, Singapore is an annual research publication by PUB, Singapore's National Water Agency. The publication can be viewed or downloaded from the PUB website.

Acknowledgements

Special thanks to our research collaborators and to PUB colleagues from the various departments for their contributions.

This publication would not have been possible without the support, ideas and good cheer from colleagues from PUB's Technology Department.

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Welcome Message

> “In PUB, we have always been cognizant that it will be high technology and clever innovation that would allow us to continue providing the high-quality water that our customers demand.”

Dear readers,

You hold in your hands the 10th edition of “Innovation in Water, Singapore”, our annual chronicle of significant research and development in the water domain. To mark this milestone, the editors have taken special effort to put together a bumper issue for your reading pleasure.

In addition to the customary news, updates and features of ongoing activities, this issue takes a look back on a decade of R&D in PUB and the breakthroughs that came along. At the same time, we cast our sights forward, over the horizon, to the future possibilities that beckon as we continue to seek new innovations.

PUB retains crystal clarity when we endow or engage in R&D. Quite plainly, every penny we expend on research and development must (a) increase water resources, (b) reduce production cost and/or (c) enhance water security and system resilience. Only then can we be assured that expensive research serves to further PUB’s mission.

In PUB, we have always been cognizant that it will be high technology and clever innovation that would allow us to continue providing the high-quality water that our customers demand. And it will be technology and innovation that would let us to collect and to clean our waste water, and therefore continue to keep our land, rivers, lakes and seas clean and hospitable.

Without a doubt, enduring water security for Singapore lies with desalination and reuse. So naturally, these are key focal areas for our R&D. But they are, by no means, the only fields in which we prospect for advances. Network surveillance, product quality assurance, automated systems, data analytics, demand management — just to name a few — are all places where we think clever science and high technology can bring game-changing improvements.

Because the heavens do not give us enough water or the space to keep it, Singapore has to depend on human ingenuity to quench our thirst. In order to achieve this and to sustain good and lasting outcomes, we have invested and will continue to bring significant resources to bear in water-related scientific research, in nurturing human talent, and in actively developing a thriving water industry.

Our quest is a never-ending one. You can be sure of it.

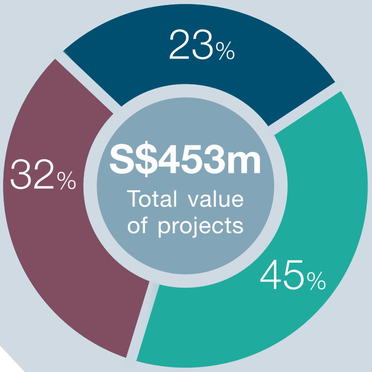
Ng Joo Hee
Chief Executive, PUB

R&D in Numbers

Since 2002, PUB, together with stakeholders dedicated to solving Singapore's water challenges, have collectively invested nearly half a billion dollars in water R&D. These range from fundamental, proof-of-concept studies to demonstration-scale trials in operational domains across the water loop. PUB works closely with its collaborators to de-risk and scale up promising technologies. As a result, one in every two projects carried out under PUB's Research & Development Fund progresses to implementation or the next development phase.

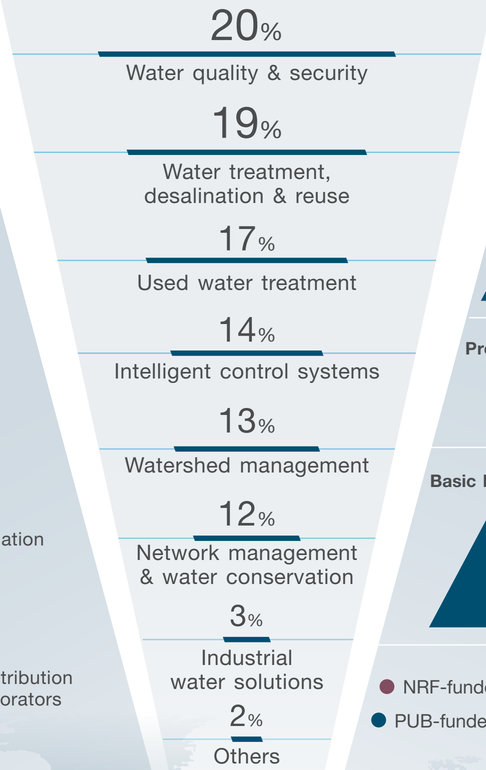
R&D INVESTMENT

(since 2002)



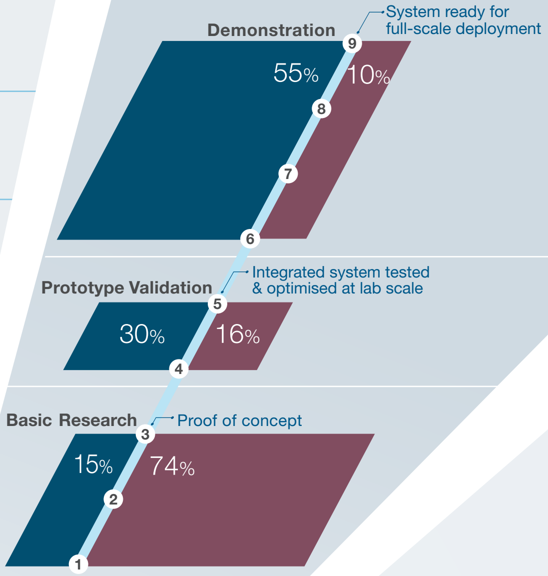
- ● National Research Foundation (NRF) funding
- ● PUB funding
- ● In-kind contribution from collaborators

ACROSS THE WATER LOOP



ACROSS THE TECHNOLOGY READINESS SPECTRUM

Spectrum comprises 9 technology readiness levels[a] (TRLs)



- ● NRF-funded projects[b]
- ● PUB-funded projects[b]

613 projects

in collaboration with partners from **27 countries**

88% of projects[b] increase in TRL when completed

ONE IN 2 completed projects[c] progress to implementation or the next development phase

---

[a] Each TRL corresponds to a specific R&D stage.

[b] Refer to projects that were completed in 2013 or later.

[c] Refer to projects funded under PUB's Research & Development Fund.

Statistics valid as at Dec 2017

Targets & Focus Areas

PUB “short-circuits” the natural water cycle through desalination and water reuse, and is one of the few utilities in the world that manages this engineered cycle in its entirety. The resultant scope of operations spans seven technical domains.

PUB has identified areas of research focus in each domain to help ensure reliable and sustainable operations in the long term. All efforts are aimed at achieving at least one of PUB’s overarching R&D goals.

OVERARCHING R&D GOALS

PUB adopts an outcome-focused and technology-neutral approach to R&D

Target
Operational or R&D goals

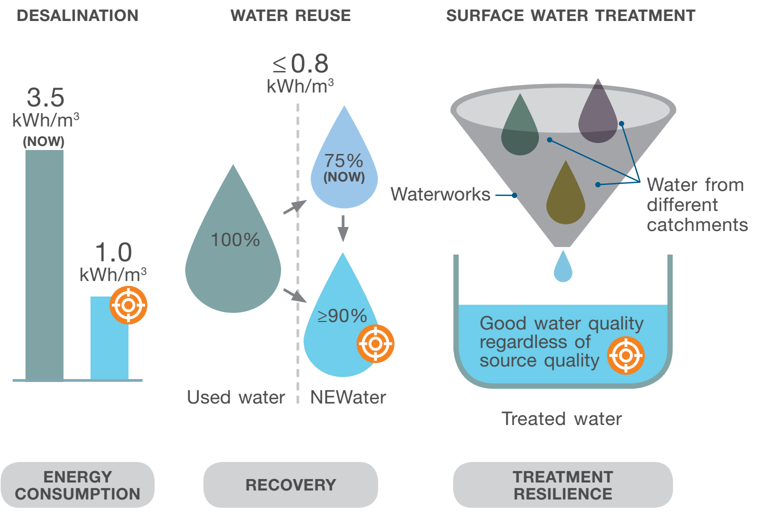
R&D area of interest
Technologies/solutions that can potentially help PUB meet its operational targets in the identified domains

Work in progress
Ongoing R&D efforts. New technologies/solutions that have the potential to be an improvement over those being trialled (in terms of performance, durability, footprint and/or cost) are also welcome

Water Treatment, Desalination & Reuse

Target · R&D area of interest · Work in progress

The challenges faced in producing potable water varies with the type of source water. Seawater and used water streams offer a potentially inexhaustible supply of water, but the current desalination energy requirements and NEWater recovery efficiencies pose barriers to their sustainable use. For surface water treatment, a key challenge is the unpredictability of water quality in urban catchments. To ensure that product water consistently meets drinking water standards, processes must be able to treat all types of feed water.



Alternative separation technologies
- Electro-deionisation

Ultra-permeable membranes
- Biomimetic membranes
- Synthetic materials

Blue energy
- Pressure retarded osmosis
- Reverse electrodialysis

Process improvements
- Electrodialysis reversal-reverse osmosis
- Flow reversal

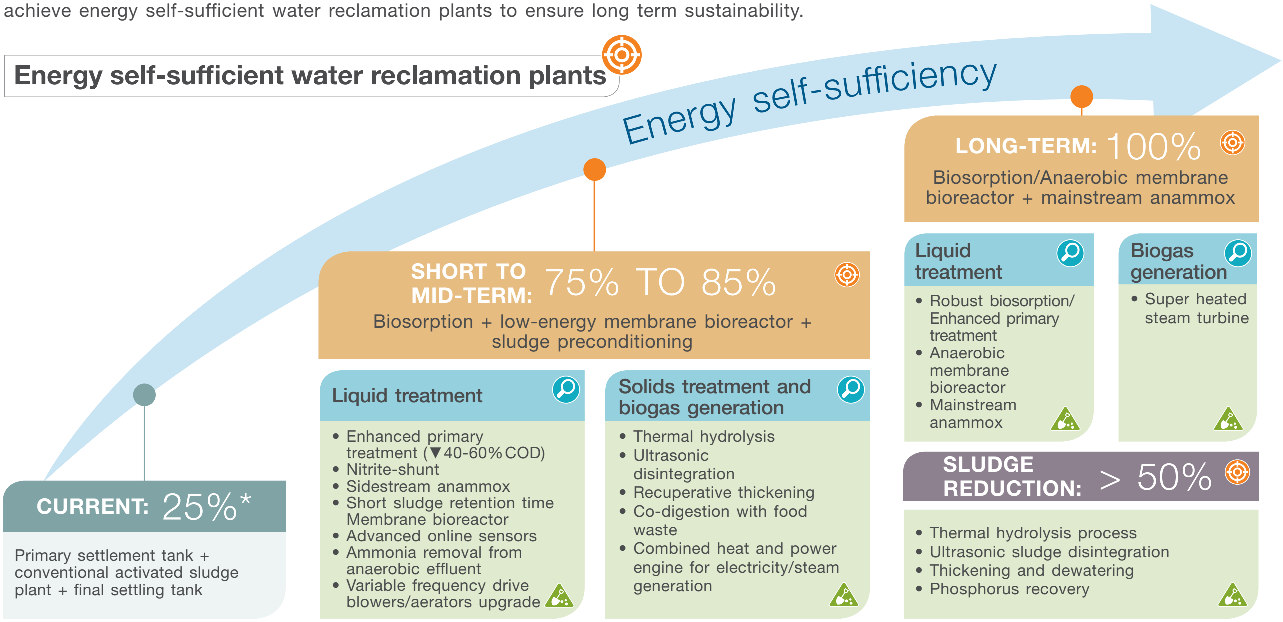
Improved pre-/post-treatment
- Advanced oxidation
- Ultrafiltration/ Microfiltration membrane improvements
- Ion exchange

Used Water Treatment

Target | R&D area of interest | Work in progress

Increasing water demand, energy costs and land scarcity underscore the need for technological breakthroughs in used water treatment. To this end, PUB is actively looking at technologies that have the potential to significantly reduce energy consumption and chemical usage in liquid stream treatment, and processes that produce more biogas and generate less sludge in solids treatment. To further reduce the sludge footprint, pre-treatment methods to improve the rate of sludge destruction in digesters are also being explored. Ultimately, PUB aims to achieve energy self-sufficient water reclamation plants to ensure long term sustainability.

Energy self-sufficient water reclamation plants



CURRENT: 25%*

Primary settlement tank + conventional activated sludge plant + final settling tank

SHORT TO MID-TERM: 75% TO 85%

Biosorption + low-energy membrane bioreactor + sludge preconditioning

Liquid treatment
- Enhanced primary treatment (▼40-60% COD)
- Nitrite-shunt
- Sidestream anammox
- Short sludge retention time Membrane bioreactor
- Advanced online sensors
- Ammonia removal from anaerobic effluent
- Variable frequency drive blowers/aerators upgrade

Solids treatment and biogas generation
- Thermal hydrolysis
- Ultrasonic disintegration
- Recuperative thickening
- Co-digestion with food waste
- Combined heat and power engine for electricity/steam generation

LONG-TERM: 100%

Biosorption/Anaerobic membrane bioreactor + mainstream anammox

Liquid treatment
- Robust biosorption/ Enhanced primary treatment
- Anaerobic membrane bioreactor
- Mainstream anammox

Biogas generation
- Super heated steam turbine

SLUDGE REDUCTION: > 50%
- Thermal hydrolysis process
- Ultrasonic sludge disintegration
- Thickening and dewatering
- Phosphorus recovery

based on full-scale operational data from Ulu Pandan Water Reclamation Plant

Water Quality & Security

Target | R&D area of interest | Work in progress

PUB aims to achieve real-time water quality monitoring through the development and implementation of in-situ sensors capable of rapid, online detection of microbial, chemical and surrogate parameters. Given the expanding range of contaminants of emerging concern, there is also a need to conduct robust risk assessment to ensure that operational decision-making is supported by a strong scientific basis in the absence of regulatory standards.

DETECTION
of contaminants

In-situ sensors

E.G.
- Parameter-specific sensors
- General indicators of water quality
- Bio-sensors
- Water quality fingerprinting

Lab-based
- Target analysis
- Non-target analysis

Desired qualities for sensor-based detection

RAPID Within minutes

ONLINE Continuous monitoring

PORTABLE Monitoring anytime, anywhere

INTEGRATED Multi-parameter sensors

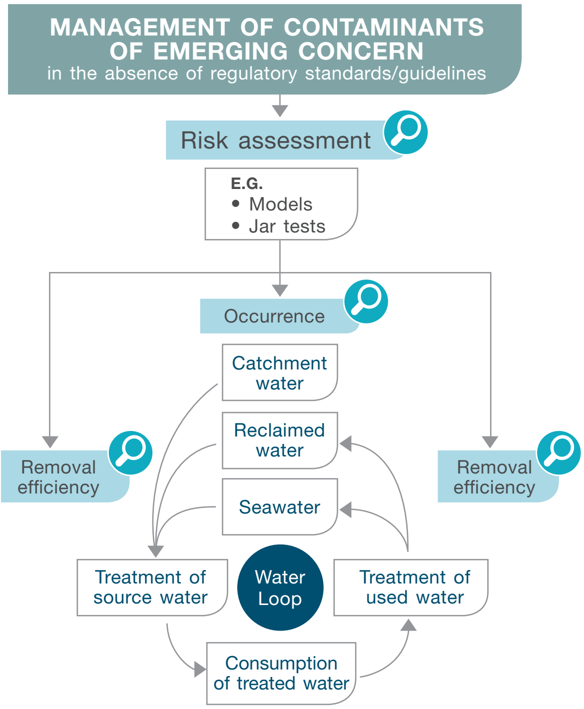
AUTOMATED Zero or minimal human intervention required

Desired qualities for lab-based detection

SENSITIVE

HIGH THROUGHPUT

AUTOMATED



MANAGEMENT OF CONTAMINANTS OF EMERGING CONCERN
in the absence of regulatory standards/guidelines

Risk assessment

E.G.
- Models
- Jar tests

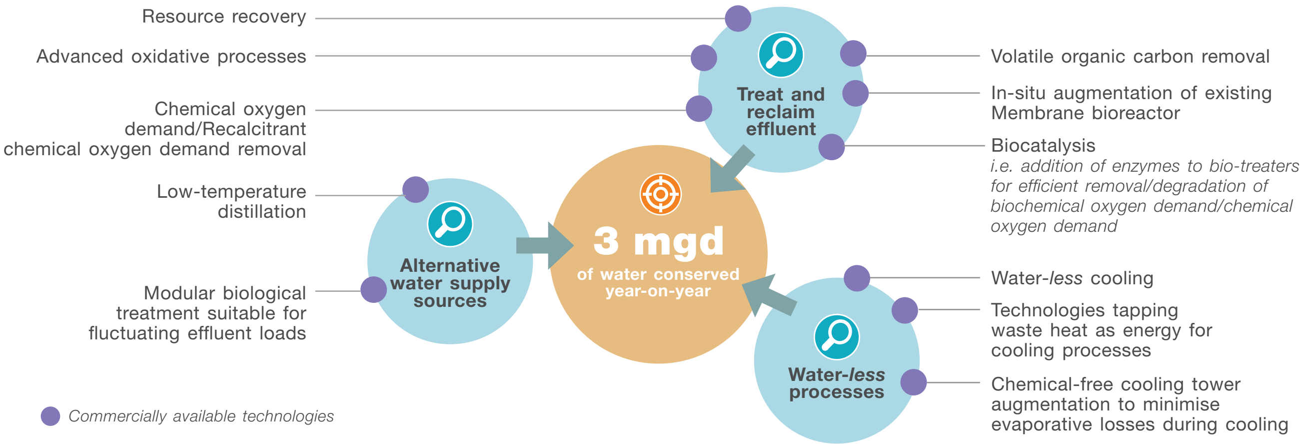
Industrial Water Solutions

Target | R&D area of interest | Work in progress

By 2060, up to 70% of Singapore's water demand will come from the non-domestic sector. PUB aims to reduce industrial water consumption by incentivising the development of solutions that target water-intensive industrial processes, and encouraging the adoption of these solutions. Key focus areas include the development of water-*less* processes, increasing recycling of treated effluent, and the use of alternative sources of water (e.g. seawater) for cooling. In addition, synergies gained from the process, such as the recovery of valuable resources from the reuse of industrial waste water, increase the value proposition of industrial water solutions and therefore warrant R&D.

Target Industries

Power Generation | Semiconductors | Petrochemicals | Pharmaceuticals | Food & Beverage



Resource recovery

Advanced oxidative processes

Chemical oxygen demand/Recalcitrant chemical oxygen demand removal

Low-temperature distillation

Modular biological treatment suitable for fluctuating effluent loads

Treat and reclaim effluent

Alternative water supply sources

3 mgd of water conserved year-on-year

Water-*less* processes

Volatile organic carbon removal

In-situ augmentation of existing Membrane bioreactor

Biocatalysis
i.e. addition of enzymes to bio-treaters for efficient removal/degradation of biochemical oxygen demand/chemical oxygen demand

Water-*less* cooling

Technologies tapping waste heat as energy for cooling processes

Chemical-free cooling tower augmentation to minimise evaporative losses during cooling

● *Commercially available technologies*

Watershed Management

Target | R&D area of interest | Work in progress

Increasing urbanisation and changing climatic conditions result in higher runoff during rain events. However, expansion of drainage infrastructure is constrained in land-scarce Singapore. There is therefore a need to explore intelligent watershed management technologies coupled with forecasting and warning systems to enhance flood resilience. Concurrently, rainwater is harvested on a large scale for water supply through collection and storage in ponds and reservoirs. To ensure that water quality remains good for potable water production, PUB invests in technologies to monitor, predict and manage levels of nutrients, algae and other contaminants in its catchments and reservoirs.

QUALITY

Ensure that reservoir water quality is good for potable water production.

QUANTITY

Enhance flood resilience of development and safeguard the integrity of drainage system.

Intelligent watershed management (data mining & analytics)

- Predictive drainage and flood management
- Hydrometeorological monitoring
- Data analytics for strategic planning and maintenance of drainage infrastructure
- Enhanced water quality modelling tools and autonomous real-time prediction platform

Watershed water quality and aquatic ecology management & modelling

- Algae monitoring and early warning systems
- Nutrient removal system in catchment
- Macrophyte restoration and biomanipulation
- Water quality monitoring systems
- Prediction of algae and metabolite levels
- Efficient algae control system

Climate change modelling

- Predictions under uncertainties and extreme weather patterns
- Flood risk assessment and cost benefit analyses for policy and decision making
- Water-sensitive urban design and adaptive infrastructure

Network Management & Water Conservation

◎ Target 🔍 R&D area of interest ▲ Work in progress

As Singapore expands its water infrastructure to meet increasing water demand, PUB faces the challenge of maintaining the current networks, and extending the water supply and used water networks within an already congested underground environment. To maintain service standards, PUB will leverage technology for remote monitoring of water quality and network pressure, advanced leak detection and diagnostic forecasting of asset failure. PUB also aims to encourage water conservation by providing more accessible and granular consumption data to customers through smart metering and water-saving devices.

Water Supply Network

INTEGRATED ◎

Develop synergies across data platforms to improve situational awareness and operational efficiency

- 🔍 **Same open protocols and reporting standards** for all network sensors, wireless communications and analytics tools
- 🔍 **Analytics tools** intuitively combine and analyse different sources of data

INTELLIGENT ◎

Generate data-driven insights to optimise prediction, prevention and response. Employ automation to enhance workplace productivity and safety

- 🔍 **Automate** laborious/repetitive tasks and deploy **advanced robotics** for pipe repair works
- 🔍 Automatically identify cause of any **pressure and water quality anomalies**
- ▲ Accurate **leak detection** using localised in-situ sensors and aerial imaging
- ▲ **Digitise** analogue/offline meter readings to facilitate data analytics and automatically identify suspected water leaks or faulty meters

RESILIENT ◎

Anticipate and respond to system faults and attacks with minimal disruption to network operations

- 🔍 **Risk-based asset management** and condition assessment tools to schedule high risk pipes for replacement before failure occurs
- ▲ Predictive **water quality and pressure models** from source to tap
- 🔍 **Generate operating scenarios** and automatically recommend the optimal approach to minimise disruption of supply to customers

INTERACTIVE ◎

Empower end-users to participate actively in protecting Singapore's water resources

- ▲ Provide customers with **high-resolution consumption data** to better understand and manage their water usage
- ▲ Develop and implement low-cost **smart water efficient devices** to drive behavioural changes

Used Water Network

NOWCAST & FORECAST SEWER WATER LEVELS ◎

Sewer analytics & modelling system 🔍

- Provide first response advice and location-specific information
- Monitor flow conditions and analyse high-flow points
- Optimise sewer cleaning and maintenance regime
- Optimise network performance through inflow and infiltration source reduction
- Recommend capacity enhancements where needed

ASCERTAIN RISK & IMPACT OF NEW TRADE PREMISES ◎

Trade effluent module 🔍

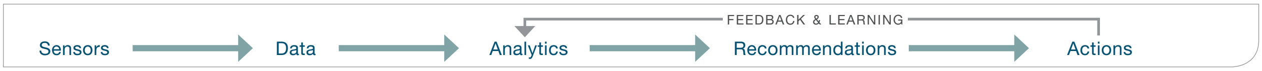
- Categorise risk and impact of trade premises
- Monitor and alert operators to issues
- Predict limit breaches and provide alerts
- Identify areas for illegal discharge investigations

TIMELY, APPROPRIATE AND COST-EFFECTIVE MAINTENANCE ◎

Asset condition management 🔍

- Understand the structural condition, performance and deterioration pattern of assets
- Facilitate planning for asset renewal and repair
- Better anticipation of asset failure

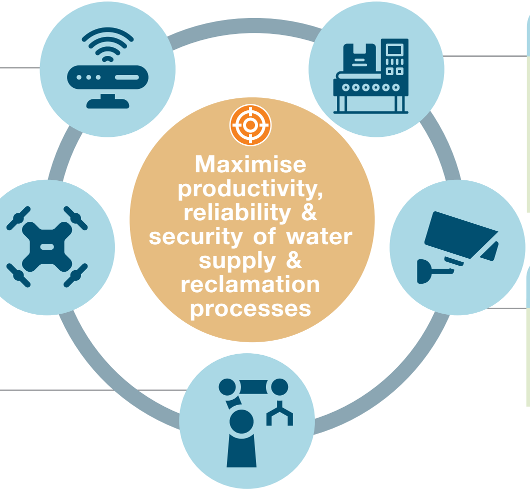
Workflow envisioned for used water management systems



Intelligent Control Systems

◎ Target 🔍 R&D area of interest ▲ Work in progress

The rapidly evolving digital landscape, coupled with a smaller but increasingly educated workforce, presents opportunities for PUB to harness smart technologies for more efficient control and operation of its water systems. To this end, PUB is exploring technologies on robotics, sensors and network communications, system automation, and virtual modelling and predictive analyses, that could help to maximise productivity and enhance operational reliability and security within the water loop.



◎ **Maximise productivity, reliability & security of water supply & reclamation processes**

Sensor network/communication for remote monitoring 🔍 ▲

- Internet of things sensors
- Data connectivity and telemetry protocols
- Secured communication protocols
- Cybersecurity

Robotics for inspection/ surveillance 🔍 ▲

- Unmanned aerial vehicle / drones in GPS-denied environment
- Artificial intelligence in remote operated vehicles

Robotics for maintenance and sampling 🔍 ▲

- Automated in-pipe inspection and localised repair and tank cleaning
- Multipurpose unmanned surface vessel

Centralised control and automated operations for plants 🔍 ▲

- Supervisory control and data acquisition
- Sensors and control system
- Building information modelling
- Data analytics for predictive maintenance
- Digital twin for whole-plant simulation

Intelligent CCTV system for remote monitoring/supervision 🔍 ▲

- Hyper-spectral and thermal cameras and sensors
- Analytical CCTV for anomaly tracking
- Geofencing and positional tracking

Collaborate with Us!

PUB welcomes research collaborations that are aligned with the organisation's mission: to ensure an adequate, efficient and sustainable supply of water. We offer a range of support comprising research funding, testbed opportunities and commercialisation support to bring your ideas to fruition.

FUNDING SUPPORT (PUB)

A

☑ **Key criteria** **Target reseach area(s)** **Openings** **Application platforms** **Featured project**

Research & Development (R&D) Fund

Facilitates R&D to increase water resources, keep operational costs competitive, and manage water quality and security

☑ Applied R&D with potential for implementation

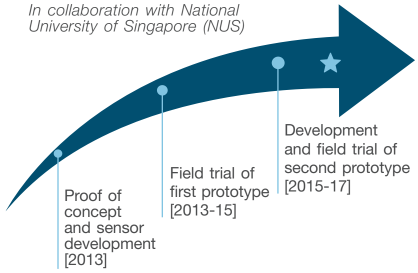
PUB's R&D **Targets & Focus Areas**

Ongoing application

Indicate interest to table a proposal at *pub_research@pub.gov.sg*

Microbial electrochemical sensor for the detection of heavy metals and cyanide in used water network

In collaboration with National University of Singapore (NUS)



★ *Development of commercial prototype is ongoing under the Competitive Research Programme (Water) fund. Commercialisation plans for mass deployment of 100 units underway.*

Industrial Water Solutions Demonstration Fund (IWSDF)

Facilitates the execution of high-impact and innovative projects to treat and reclaim industrial used water for process reuse

☑ Water consumption should exceed 10,000 m³/mth

Aim for at least 5% reduction in water consumption through reuse

Technologies that

- are validated and ready for demonstration-scale implementation
- showcase innovation in the technology itself, and/or its application

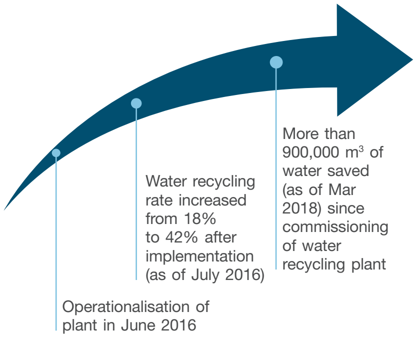
PUB's R&D **Targets & Focus Areas** for Industrial Water Solutions

Ongoing application

Download Project Assessment Form from *www.pub.gov.sg/research/industrialwatersolutions/funding.* Submit completed form through *pub_one@pub.gov.sg*

Ceramic microfiltration-reverse osmosis-based water recycling plant

In collaboration with Singapore Refining Company



FUNDING SUPPORT (NRF)

Competitive Research Programme (Water)

Support (a) basic and applied R&D in strategic areas, and (b) translation of validated concepts

☑ Project to be carried out in Singapore

🔍 Varies across Requests-for-Proposal (RFPs); broad aim of helping PUB meet its operational targets

TYPES OF RFPs	
CHALLENGE Address critical barriers and enable progress in the field. May involve achieving stretch targets	**DIRECTED** Build capability under an identified research theme (e.g. energy efficiency in used water treatment)
RESEARCH PROGRAMME Solicit proposals exploring complementary technical areas	**OPEN** Bottom-up channel to solicit a diverse range of water-related solutions without specific research themes

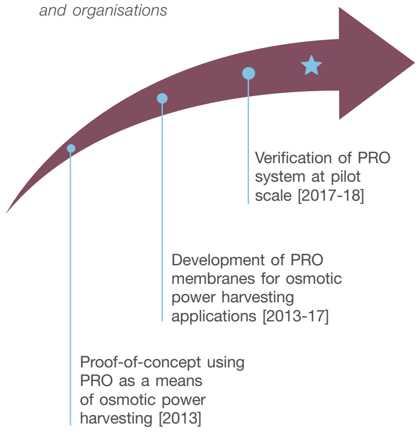
📣 Periodic RFPs, announced through

- Integrated Grant Management System
  researchgrant.gov.sg
- PUB website
  pub.gov.sg/research/collaboration
- Email notification

✉ Request to be included in mailing list at *pub_research@pub.gov.sg*

Pressure retarded osmosis (PRO)

In collaboration with various institutions and organisations



Verification of PRO system at pilot scale [2017-18]

Development of PRO membranes for osmotic power harvesting applications [2013-17]

Proof-of-concept using PRO as a means of osmotic power harvesting [2013]

★ *Verification of PRO system at demonstration scale ongoing under NRF's Urban Solutions and Sustainability Integration Fund.*

Living Lab (Water)

Incentivise the adoption of new technologies, facilitating commercialisation

☑ Involve a solution provider and an adopter

Carried out in Singapore

Only Singapore-registered businesses and organisations are eligible

Grant quantum will consider strength of business plan (in terms of potential revenue generated and jobs created)

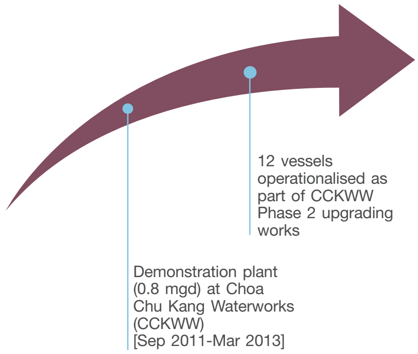
🔍 Project shall involve the demonstration of a water technology that is close to operational stage by an adopter. The technology trialled should have high potential to help PUB meet its operational targets

📣 Ongoing application

✉ Joint application* by technology provider and adopter. Indicate interest at *pub_globalhydrohub@pub.gov.sg*

Ceramic membranes for surface water treatment

In collaboration with PWN Technologies



12 vessels operationalised as part of CCKWW Phase 2 upgrading works

Demonstration plant (0.8 mgd) at Choa Chu Kang Waterworks (CCKWW) [Sep 2011-Mar 2013]

* *Technology provider can be conditionally awarded prior to the appointment of an adopter*

B

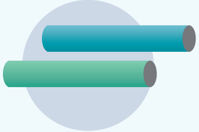
TESTBEDDING OPPORTUNITIES

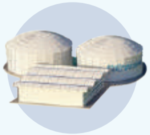
PUB's **operational and R&D-dedicated infrastructure** is available to host and facilitate your research. Technology developers looking to increase their product's operational readiness and relevance can apply to carry out testbeds at our live installations and field sites. Facilities dedicated to desalination and freshwater research are also available.

Operational Installations & Sites

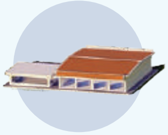

Waterworks


Water Reclamation Plants


Potable & Used Water Networks


NEWater Factories


Reservoirs

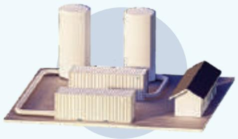

Variable Salinity Plant

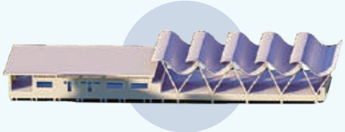

Desalination Plant

✓ Actual operating environments

✓ Technical support from ground staff

R&D-dedicated Facilities


Tuas R&D Facility
Desalination technologies


Van Kleef Centre
Freshwater research

✓ Laboratory amenities* and research/testbed spaces

** Applies to Van Kleef Centre only*

C

TRANSLATION & COMMERCIALISATION

The **Singapore Water Exchange** in WaterHub supports the last phase of technology development – the translation of validated prototypes to operationally-ready products – and the commercialisation of these technologies.

TECHNOLOGY TRANSLATION

Through our partnerships with translational facilities, technology developers can engage experts in engineering design, and access fabrication and pilot testing systems to overcome translational gaps.

COMMERCIALISATION

Market entry of operationally-ready technologies, and the business growth needed to ensure the viability of these products, are facilitated through the matchmaking of technology developers with key market stakeholders.

GENERAL ENQUIRIES

A B *PUB_Research@pub.gov.sg*

C *PUB_WaterHub@pub.gov.sg*

Scan for more information

FEATURE STORY

Journey towards water sustainability

Ensuring a safe and adequate supply of water has been a top priority for Singapore since its independence more than half a century ago. As a young nation with limited natural water resources, Singapore knew the only way to ensure its survival was to invest in technology and innovation to find solutions.

Singapore first experimented with membrane technology for water recycling in the 1970s. While the technology was not mature enough to be implemented at that time, the experience laid the foundation for the successful implementation of NEWater nearly three decades later.

FIG. 1: Bedok NEWater Plant Opening Ceremony in February 2003

In 2001, Singapore brought its water, sewerage and drainage functions under PUB. Reconstituted as Singapore's National Water Agency, this enabled PUB to streamline the management of Singapore's water supply in a holistic, integrated and coordinated manner across the three functions.

The launch of NEWater in 2003 (Fig. 1) was a pivotal milestone in PUB's R&D journey. It enabled PUB to close the water loop, and was the first large-scale technological solution that was realised by PUB. Its success brought PUB widespread recognition as one of the leading water utilities globally. More importantly, it strengthened PUB's belief that technological solutions could provide the answers to its challenges.

Armed with the experience and confidence gained from NEWater's success, PUB's approach towards R&D underwent a radical shift. PUB decided that it would build up its internal R&D capabilities and work with local and international partners to co-develop technological solutions.

> “NEWater's success strengthened PUB's belief that technological solutions could provide the answers to its challenges.”

A UTILITY SHAPED BY INNOVATION

We explore how ongoing innovation has shaped PUB's operations over the years, strengthening the robustness and resilience of Singapore's water supply system.

Water Treatment

As catchment areas become increasingly urbanised, resulting in greater fluctuations in surface water quality, PUB's waterworks have progressed from conventional sand filtration systems to membrane filtration using either polymeric or ceramic membranes (Fig. 2). Ozone-biological activated carbon filters are also increasingly used to strengthen the disinfection process and improve the quality of treated water. PUB is now exploring the feasibility of enhancing its pre-treatment processes with ion exchange technology to better manage challenging source waters with elevated total organic carbon concentration.

Reservoir Management

Early methods of algae management, such as the use of fish cage culturing in the 1970s, were labour-intensive. Today, advanced monitoring and treatment technologies such as the use of robotic sensors (Fig. 3) and ultra-low frequency treatment are employed to monitor water quality and manage algae efficiently. Through the restoration of habitats in reservoirs, PUB is looking to leverage healthy aquatic ecosystems to help suppress algae proliferation naturally.

Drainage Management

The use of sensor technology, as well as advanced computational and modelling tools, has allowed PUB to better manage the increasing complexities of Singapore's urban drainage system. Presently, drainage water levels are remotely monitored via in-situ sensors (Fig. 4), allowing flood risks to be assessed in real-time for better operational response. The design of the drainage system is also supported by simulation tools that model complex hydrological and hydraulics behaviours. This is in contrast to the reliance on manual calculations and static data prior to the advent of digital technology.

Water Quality Monitoring

Water quality analysis has traditionally relied on tedious, time-consuming culturing and analytical methods. Over the years, PUB has automated its processes, developed rapid and mobile detection systems, and enabled on-site analysis for greater monitoring efficiency (Fig. 5). These have allowed PUB to increase the number of monitoring parameters significantly, enhancing our water security.

Water Supply Network

Following the Second World War, the Government undertook a massive effort to replace public standpipes with piped and metered supply to buildings as the population grew. The use of a master meter to track total water usage of buildings then progressed to the installation of dedicated meters for individual units within buildings to facilitate fairer billing practices. PUB is now studying the performance of meters equipped with automatic meter reading (AMR) capabilities. These advanced meters (Fig. 6) will provide consumers with digital consumption data in near real-time, empowering households to identify potential leaks early and monitor daily consumption behaviour to save on utility bills.

Used Water Treatment

PUB's water reclamation plants (WRPs) are traditionally land- and energy-intensive. Efforts to derive energy savings from improvements in used water treatment processes and resource recovery, and develop energy self-sufficient WRPs that employ advanced treatment technologies with leaner footprint requirements are in full swing. The upcoming Tuas WRP (Fig. 7), a key component of the Deep Tunnel Sewerage System Phase 2, is anticipated to be the world's largest water reuse facility that runs on a membrane bioreactor-driven process, and the first in Singapore to harness synergies from a co-located Integrated Waste Management Facility to achieve energy self-sufficiency. Efforts to centralise and compact Singapore's used water infrastructure will also see its existing land footprint halved by 2025.

FIG. 2: Ceramic membrane installation at Choa Chu Kang Waterworks (CCKWW)

FIG. 4: Water level sensor installed in a canal

FIG. 6: AMR-enabled inductive meter

FIG. 3: A Smart Water Assessment Network (SWAN) robot performing water quality profiling

FIG. 5: PUB's mobile laboratory enables water quality analysis to be carried out on the go

FIG. 7: Artist impression of the upcoming Tuas WRP

TECHNOLOGY HIGHLIGHTS

Through years of research and close collaboration with the industry and academia, PUB's investments in R&D have borne fruit. An ever-increasing list of technological solutions have been lab-tested, test-bedded and eventually implemented in PUB's operations. We look back on three examples.

FIG. 8: Fish Activity Monitoring System (FAMS)

“With FAMS, the monitoring of fish activity –a crucial first-line assessment of treated water quality – is now fully automated and centralised,” said PUB operator Philip Lee. “PUB can provide timely intervention to safeguard water security, and increase our operational productivity.”

Fish Activity Monitoring System (FAMS)

FAMS is an automated system that pumps a continuous sample stream of treated water through an aquarium housing tiger barbs (Fig. 8). Video footage of the fish is captured, and their mortality rate is observed via image analysis software. Operators are alerted if there are changes in the mortality rate which indicate possible changes in water quality. This way, PUB is able to remotely monitor fluctuations in treated water quality from a centralised location, negating the need for manual inspections.

Since the first pilot test in 2006, FAMS has undergone significant improvements in terms of detection sensitivity, reliability and operability. The successful initial deployment of seven units at Nanyang Service Reservoir in 2010 has been expanded to 45 units island-wide today, providing round-the-clock surveillance to strengthen the monitoring of traditional water quality parameters such as pH and conductivity. In 2016, ZWEEC Analytics and PUB pilot-tested the second generation FAMS, which features an added ceramic filtration module to remove particles before water enters the fish tank, ensuring good visual clarity for optimal performance.

“With FAMS, the monitoring of fish activity – a crucial first-line assessment of treated water quality – is now fully automated and centralised,” said PUB operator Philip Lee. “PUB can provide timely intervention to safeguard water security, and increase our operational productivity.”

The success of FAMS and its good track record in Singapore has also enabled ZWEEC Analytics to break into overseas markets such as Australia, China and Taiwan.

Keppel Marina East Desalination Plant (KMEDP)

PUB carried out a demonstration study in 2007 to explore the feasibility of a facility capable of treating both brackish water and seawater using reverse osmosis (Fig. 9). This dual-mode technology has the potential to allow water from fringe estuaries to be harvested viably.

Accorded the top prize in the Applied Research category at the International Water Association's Project Innovation Awards in 2010, this technology became PUB's first technology patent in 2011. After proving the technology's

FIG. 9: Variable Salinity Plant at Sungei Tampines

As a dual-mode plant, KMEDP will have the capability to treat both freshwater from Marina Reservoir and seawater.

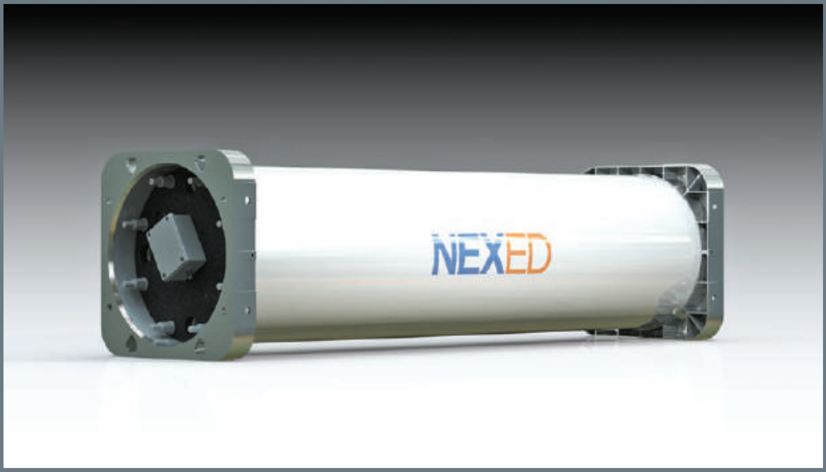


FIG. 12: Evoqua's NEXED module, which is currently being optimised at the Tuas R&D Facility

reliability through the demonstration study at Sungei Tampines, it will be implemented full-scale in the 30 mgd KMEDP (Fig. 10), which is expected to complete in 2020.

As a dual-mode plant, KMEDP will either treat freshwater from Marina Reservoir or desalinate seawater, depending on wet or dry weather conditions. It will be another step forward in enhancing the drought resilience and sustainability of Singapore's water supply.

Electro-deionisation (EDI) Technology

Desalination taps on an unlimited and weather independent source of water, and is pivotal to Singapore's long-term water security. However, traditional reverse osmosis-based desalination would be unsustainable in the long run as the energy required to pump seawater through membranes is relatively higher. PUB has been intensively researching more energy-efficient desalination solutions, and EDI technology – a low-pressure process that uses an electric field to remove salt ions from seawater – is a frontrunner in helping PUB achieve its mid-term energy targets.

Using prototype modules developed by then Siemens Water Technologies (now Evoqua Water Technologies), EDI desalination technology was successfully trialed with an energy consumption of 1.65 kWh/m^3 at a 50 m^3/day pilot plant (Fig. 11). This is half the energy required by conventional seawater reverse osmosis processes. The technology was commercialised for brackish water applications (Fig. 12) in 2014, and is currently being scaled-up at PUB's R&D facility in Tuas where it is slated to be trialed at a 3,800 m^3/day facility by 2018. If the ongoing efforts to optimise and operationalise the treatment process prove successful, PUB could scale it up further and operate a 10,000 m^3/day EDI train alongside conventional desalination processes at the Tuas Desalination Plant.

FIG. 11: An early electro-deionisation prototype module

"One of the lessons learnt from our experience with EDI technology is that there is a huge, and sometimes even paralysing gap between a validated prototype and a design that is scalable for commercial applications," said PUB project manager Roderick Sih, referring to the challenge commonly faced in optimising a technology for mass production. "The progress made so far shows us that, with perseverance and a strong collaborative approach, barriers in technology translation can be overcome."

> "With perseverance and a strong collaborative approach, barriers in technology translation can be overcome."

FIG. 10: Artist impression of the Keppel Marina East Desalination Plant

EXTENDING THE GLOBAL REACH OF PUB'S RESEARCH

Partnering the world

As a small nation, Singapore stays connected to the world, keeping abreast of the latest technological developments, accessing expertise in novel research fields, and forging partnerships with other like-minded utilities and institutions.

A member of the Global Water Research Coalition (GWRC), PUB participates in regular exchanges with leading institutions in water research. This helps PUB go beyond relying solely on local expertise to fill existing information gaps, and even leapfrog to address areas of emerging significance. Through the global coordination of research efforts, PUB works with partners to invest in R&D that complements the respective research agendas, tapping synergies to strengthen research efforts in unexplored areas and create higher value with every dollar spent.

PUB also sits on the committees of organisations such as the Water Research Foundation, the International Water Association, and the International Desalination Association. This allows it to keep up with international best practices in specific technical areas. Designated as a World Health Organization (WHO) Collaborating Centre since 2012, PUB was directly involved in the development of the WHO *Guidelines for Drinking Water Quality* and, more recently, the *Potable Reuse: Guidance for Producing Safe Drinking-Water* – key water quality standards that are recognised internationally and referenced by water utilities and the industry worldwide.

Welcoming the world to Singapore

Every other year, PUB welcomes the world to home soil for the Singapore International Water Week (SIWW), a global platform where innovation is co-created, discussed, shared and celebrated over a week of water events and showcases.

One of the highlights is the Lee Kuan Yew Water Prize, an international award which recognises individuals or organisations with outstanding achievements in water through the advancement of technology, science or policy. To-date, eight researchers and institutions from across the globe have been recognised for their seminal contributions in a wide range of domains such as water and used water treatment, river management, groundwater and public policy.

Discourse on the latest water innovations and trends take place over a series of technical sessions and workshops at the Water Convention.

To encourage the commercialisation of new water technologies to the market, the TechXchange was introduced in 2011 to match-make innovative technology providers with partners, buyers and investors. Complementing the forum is the Water Innovation Pavilion, an international showcase featuring solutions ranging from promising prototypes to commercially-ready technologies.

LOOKING AHEAD

Through clear thinking, sound strategy, and an iron-clad resolve to realise and implement new technology, Singapore has successfully turned its water vulnerability into a strength. However, PUB cannot afford to rest on its laurels.

To continue its foray into new and emerging areas, PUB recently launched three request-for-proposals for solutions to enhance energy efficiency in treatment processes, improve water efficiency in industries, and develop smart technologies.

Smart PUB

The digital landscape continues to change rapidly, transforming the way we live, work and play, as well as the way we manage water. Complementing Singapore's Smart Nation efforts, PUB aims to harness these technologies for improved planning and operational efficiency, building water resilience and enhancing water security.

PUB envisions that smart technologies will soon be employed to manage plant operations, which will become more challenging in the face of climate change and urbanisation. These "Smart Plants" will leverage artificial intelligence to analyse large volumes of operational data quickly for decision support and process automation, or even predict the occurrence of equipment failure. In the event of equipment failure, intuitive data libraries can offer speedy and comprehensive information to expedite rectification work. Closed-circuit television integrated with video analytics can also identify safety breaches while repair works are ongoing, and provide alerts to operators who are working away from site.

Drones and unmanned aerial vehicles will also be deployed to support reservoir management. Automating traditionally manpower-intensive tasks such as sampling and monitoring of algal blooms, and even supporting tasks such as the inspection of difficult-to-access work areas can improve the efficiency and safety of water quality management.

Ensuring a safe, secure and sustainable water-future for Singapore

Some 20 years ago, PUB embarked on an R&D journey to drive the innovation that would help ensure a safe and adequate supply of water. In the face of challenges like climate change, energy price fluctuations and increasing water demand, PUB must stay relentless in its pursuit of its long-term R&D goals – to increase water resources, reduce production cost, and enhance water security and system resilience.

All this so that the turning on of a tap – at anytime and anywhere in Singapore – will always yield potable water that is accessible for all.

FACILITIES

A living laboratory and global testbed for water technologies

Since 2006, $670 million has been committed by the Singapore Government to foster water technologies and create a thriving research community over 15 years. Today, Singapore has approximately 180 water-related companies and over 20 public and private research centres, and is widely recognised by the international water community as a living laboratory for testing water technologies.

Singapore's investments in R&D was borne out of necessity rather than choice. Faced with land constraints and a lack of natural resources, innovation was the answer to ensuring long-term water sustainability. As the national water agency, PUB manages all aspects of Singapore's water resources, and sets the direction of the country's water R&D programme to address its challenges. To accelerate the development and adoption of new water technologies, PUB proactively collaborates with local and international partners to turn promising ideas into market-ready solutions.

Upstream research centres

To translate scientific theories and principles into practical application, PUB works with upstream research centres to carry out basic and applied research. There are presently more than 10 such publicly-funded Research Centres of Excellence located in universities and tertiary institutions in Singapore. A combination of fundamental investigation and laboratory experimentation are conducted to establish proof of concept. Thereafter, prototypes are developed and tested in simulated environments through bench-scale tests.

Testbedding and demonstration sites

At the subsequent pilot and demonstration stages, PUB makes its facilities available to test new technologies under actual operating environments. More than 30 sites that cover every operational domain along the water loop are located island-wide. These comprise waterworks, water reclamation plants, NEWater factories, reservoirs, stormwater canals, water supply pipes and sewers. Water technologies are tested using actual feed water, and are validated under real-world conditions. Since 2002, PUB has supported an extensive range of testbedding and demonstration-scale projects at its facilities. Find out more about some of these projects in the accompanying infographic.

To understand how Singapore developed its reputation as a living laboratory for water technologies, one needs only to look at the unique proposition that PUB offers. Firstly, PUB is one of the few utilities in the world that manages the entire the water loop covering drinking water, used water and surface water. Secondly,

> “By adopting an open and collaborative approach towards R&D, PUB has helped create a vibrant water R&D ecosystem comprising an impressive suite of facilities and sites.”

with alternative water sources like desalination and water reuse, PUB has “short-circuited” the water loop and opened up new opportunities for operational efficiencies and improvements through technology. Thirdly, PUB welcomes novel ideas and technically sound solutions that will help it increase Singapore’s water resources, enhance water quality and security, and lower production cost.

These factors allow PUB to offer unparalleled testbedding opportunities, where almost any promising water-related technology can find relevance in its operations, and at times even multiple applications.

For example, while the Fish Activity Monitoring System (FAMS) was introduced as an early warning system for the detection of irregularities in drinking water, PUB has also tested its applicability in monitoring surface water quality. Similarly, online sensors that are tested in potable drinking water systems can also be assessed for deployment in drainage systems, while reverse osmosis systems and membrane applications can be tested for use in both water and used water treatment processes.

In an industry that is often risk-adverse in trying out new and unproven technologies, the availability of these testbedding sites has been a boon to innovators and researchers. By sharing the costs and risks associated with the testbedding of new technologies, PUB is also able to gain the buy-in and commitment of partners to develop new water technologies, and be an early adopter of promising technologies.

Translational facilities

It is only through large-scale implementation that technology developers and end users reap the full benefits of the new technologies. Beyond providing avenues for new technologies to be validated under real-life conditions, it is crucial to accelerate the journey from technology prototyping and validation to commercialisation.

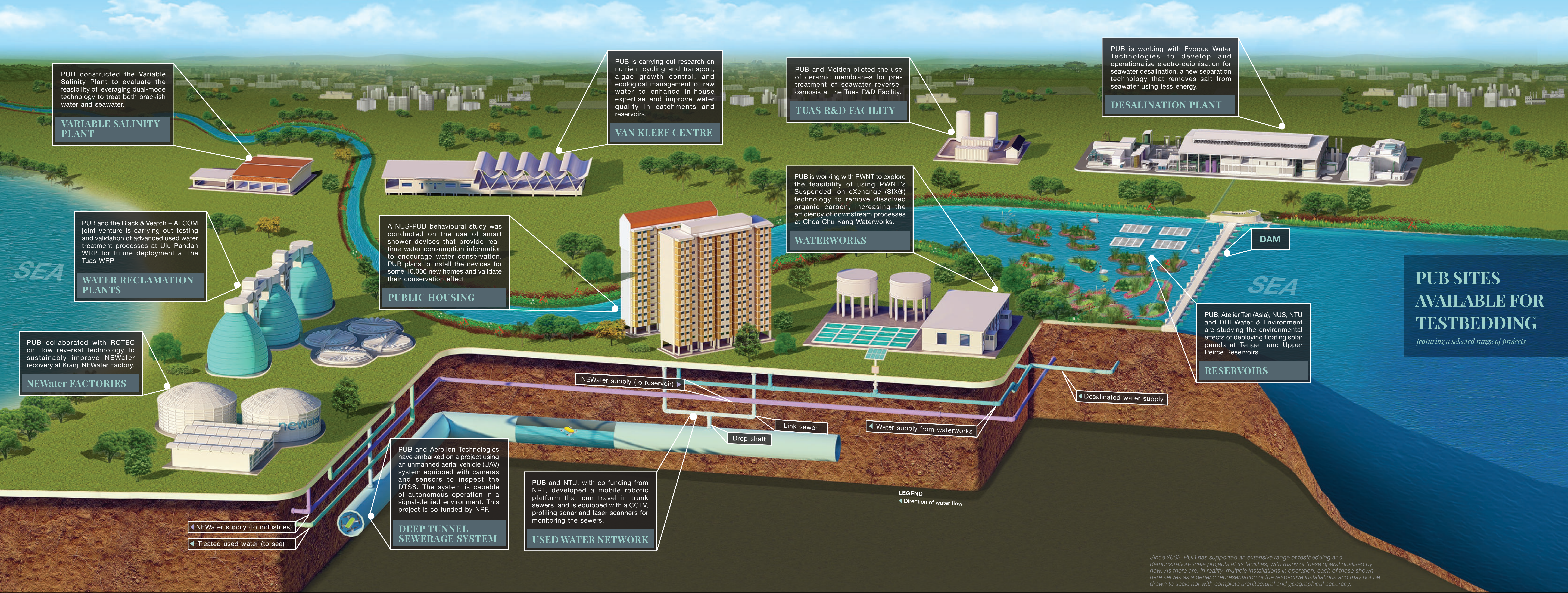
Often, the financial stakes and risks make the translation of promising research into commercialisable technologies a challenge. Researchers and technology developers may not have the practical knowledge, necessary capital or resources, and right skills to commercialise their technology.

To help ensure that efforts in fundamental and applied research do not go to waste, there are at least two translation facilities in Singapore – the Separation Technologies Applied Research and Translation Centre (START) and Ngee Ann Polytechnic’s Environmental and Water Technology Centre of Innovation (EWTCOI) – which serve as a bridge between academia and industry. These provide industry expertise and pilot-testing facilities to enable the translation of promising innovations into commercially viable products.

By adopting an open and collaborative approach towards R&D, PUB has helped create a vibrant water R&D ecosystem comprising an impressive suite of facilities and sites. Technology development in Singapore is greatly accelerated with many technology solutions showcased across the island. This has cemented Singapore’s global status as a technology enabler.

PUB SITES AVAILABLE FOR TESTBEDDING

featuring a selected range of projects



PUB constructed the Variable Salinity Plant to evaluate the feasibility of leveraging dual-mode technology to treat both brackish water and seawater.

VARIABLE SALINITY PLANT

PUB is carrying out research on nutrient cycling and transport, algae growth control, and ecological management of raw water to enhance in-house expertise and improve water quality in catchments and reservoirs.

VAN KLEEF CENTRE

PUB and Meiden piloted the use of ceramic membranes for pre-treatment of seawater reverse-osmosis at the Tuas R&D Facility.

TUAS R&D FACILITY

PUB is working with Evoqua Water Technologies to develop and operationalise electro-deionisation for seawater desalination, a new separation technology that removes salt from seawater using less energy.

DESALINATION PLANT

PUB and the Black & Veatch + AECOM joint venture is carrying out testing and validation of advanced used water treatment processes at Ulu Pandan WRP for future deployment at the Tuas WRP.

WATER RECLAMATION PLANTS

A NUS-PUB behavioural study was conducted on the use of smart shower devices that provide real-time water consumption information to encourage water conservation. PUB plans to install the devices for some 10,000 new homes and validate their conservation effect.

PUBLIC HOUSING

PUB is working with PWNT to explore the feasibility of using PWNT's Suspended Ion eXchange (SIX®) technology to remove dissolved organic carbon, increasing the efficiency of downstream processes at Choa Chu Kang Waterworks.

WATERWORKS

PUB, Atelier Ten (Asia), NUS, NTU and DHI Water & Environment are studying the environmental effects of deploying floating solar panels at Tengeh and Upper Peirce Reservoirs.

RESERVOIRS

PUB collaborated with ROTEC on flow reversal technology to sustainably improve NEWater recovery at Kranji NEWater Factory.

NEWater FACTORIES

PUB and Aerolion Technologies have embarked on a project using an unmanned aerial vehicle (UAV) system equipped with cameras and sensors to inspect the DTSS. The system is capable of autonomous operation in a signal-denied environment. This project is co-funded by NRF.

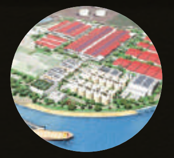
DEEP TUNNEL SEWERAGE SYSTEM

PUB and NTU, with co-funding from NRF, developed a mobile robotic platform that can travel in trunk sewers, and is equipped with a CCTV, profiling sonar and laser scanners for monitoring the sewers.

USED WATER NETWORK

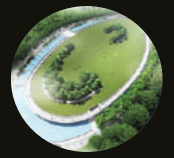
Since 2002, PUB has supported an extensive range of testbedding and demonstration-scale projects at its facilities, with many of these operationalised by now. As there are, in reality, multiple installations in operation, each of these shown here serves as a generic representation of the respective installations and may not be drawn to scale nor with complete architectural and geographical accuracy.

INTERESTING FACTS



The upcoming Tuas WRP will be the largest MBR-based plant in the world at time of commissioning, with a footprint that is 30% more compact than conventional WRPs

Choa Chu Kang Waterworks will have one of the largest installations of ceramic membranes in the world after upgrading works are completed



Keppel Marina East Desalination Plant is probably the first dual-mode plant in the world to treat both seawater and freshwater at municipal scale

Tengeh Reservoir currently houses the world's largest floating solar panel testbed in terms of the number of different photovoltaic systems deployed, covering one hectare of water surface and generating enough energy to power 250 four-room HDB flats for a year

Ulu Pandan WRP is home to a 2.75 mgd used water demonstration plant which serves as a living model of the upcoming Tuas WRP. The demonstration plant was accorded the Water/Wastewater Project of the Year Award at the 2018 Global Water Awards for its innovative use of technology in the used water treatment process

TESTBED WITH US

Scan QR code for information on testbedding opportunities

INTERVIEW

Reflections on the journey

Harry Seah is PUB's Assistant Chief Executive (Future Systems and Technology). In 1998, Seah was part of a two-man team sent to Orange County, California, to study the feasibility of introducing water reuse in Singapore. Upon his return, he spearheaded an extensive water reuse study which led to the eventual introduction of reclaimed water (termed NEWater) as a source of water in Singapore in 2003. Seah has overseen PUB's R&D efforts since then, leading the transformation of PUB into a well-respected water utility known for embracing innovation and technology.

> *"The key was to cultivate a positive energy towards R&D within the organisation. We created a safe environment by encouraging our staff to step out and take calculated risks, even if these efforts may fail."*

We often hear that water utilities are risk-adverse and reluctant to try new ideas and innovation. Yet PUB is the exact opposite. What led PUB to embrace innovation in the way it did?

As a small country with limited natural water resources, Singapore was forced by its unique circumstances to innovate to solve its water challenges. We had no choice but to invest heavily in R&D. Otherwise, our taps will run dry and Singapore will not survive.

In the early years, our NEWater success helped lay the foundation for our R&D programme because it demonstrated that with the right framework and attitude, we can tap on engineering and science to overcome challenges. It gave us the confidence to test assumptions and try out new solutions. To illustrate, years ago, we were exploring if chloramination could control biofouling in membranes. Many experts cautioned that its prolonged use would damage the membranes but no one had carried out tests to verify these claims. So we did our own tests and proved that the concern was misplaced. Chloramination is now used by PUB as a way to control membrane biofouling.

The key is to cultivate a positive energy towards R&D within the organisation. We created a safe environment by encouraging our staff to step out and take calculated risks, even if these efforts may fail. No one gets blamed for a failed project as long as it is managed to the best of their ability.

R&D takes time, effort and resources, sometimes without success. Often, this competes with the demands of day-to-day operations. How does PUB manage between the two?

Consensus among the senior management is key. In PUB, the department heads understand that if operations continue business-as-usual using today's technology, our energy consumption will quadruple and the amount of waste generated will double by 2060. This is not sustainable. As an organisation, we need to continue to innovate and find new solutions.

This shared belief on the importance of R&D did not come overnight. It took us about four to five years to get the operational departments onboard. I am proud to say that today, other than fundamental research, most of PUB's research projects are driven by our operational departments. Our Technology Department assumes the role of a facilitator, linking our engineers and scientists with the industry and academia.

Increasingly, innovation involves some degree of automation. As Head of Future Systems and Technology, how do you ensure that PUB stays at the forefront of technology while maintaining job security for your staff?

Advances in digital technology, such as the Internet of Things (IoT), data analytics and real-time computing, create new opportunities for us to manage our water system in ways that were previously not possible. Take for example drainage management. When we encounter a capacity problem with our canals, the conventional engineering solution will be to widen them. But this is not sustainable in land-scarce Singapore. Technology now allows us to monitor the water level and flow in our canals in real time, and in the near future, this could facilitate innovative solutions such as the inter-transfer of flows between drains for timely intervention.

As an organisation, we need to prepare our people to be ready to embrace these new technologies. While traditional disciplines such as engineering and science remains core knowledge to our operations as a utility, our people will need to be equipped with new skills such as computing and data analytics. In future, engineers may find themselves armed with many virtual assistants to facilitate operational decisions. These machines will learn the operating environment and, with the capture of real-time data over time, be able to predict operational trends and behaviour. All these will assist our officers to make data-driven decisions, eliminating reliance on gut feel and intuition.

Does this mean we will require less manpower in the future? No. On the contrary, I see automation and technology as a way to help us overcome the manpower constraints coming our way as Singapore's water needs increase and workforce ages.

What do you see are some of the future challenges that PUB will face? How does this shape PUB's R&D strategy moving forward?

In PUB, we set aside a budget for R&D annually and there is a good reason for that. Today's technology will only buy us time until we find better solutions. We cannot afford to be complacent.

Our goal is to meet our future water demand, which in 2060 will double, at today's energy and waste footprint or better. To this end, biology will become an increasingly important research discipline for PUB. Biological systems have evolved over billions of years, enabling organisms to thrive in their environments, so there must be something we can learn from nature to solve our water problems. We will invest to understand how biological systems work, and how applicable concepts can be imitated to achieve the engineering outcomes we want. We are already seeing some early success as evidenced by our research in biomimetic membranes.

It must have been a fulfilling journey for you over the past 20 years, to oversee the development of NEWater and to spearhead the R&D setup at PUB. What has been your greatest memory in this journey?

I was blessed with the opportunity to work on the NEWater project in 1998, although not many people wanted the job back then because it was the first of its kind in Singapore, and there were many unknowns. Fortunately, during my younger days as an engineer in the then-Ministry of the Environment, my experience working under Mr T. K. Pillai taught me that nothing was impossible if I believed in what I was doing and put my mind to the task, even if it involved experimenting and making mistakes. Armed with that mind-set, and with the structured training I received during my subsequent stint in the sewerage department, I gamely took on the challenge. I knew it was an important project for Singapore but at that time I did not fully appreciate the impact that it would make to our overall water strategy.

> *"In future, engineers may find themselves armed with many virtual assistants to facilitate operational decisions...does this mean we will require less manpower in the future? No. On the contrary, I see automation and technology as a way to help us overcome the manpower constraints coming our way..."*

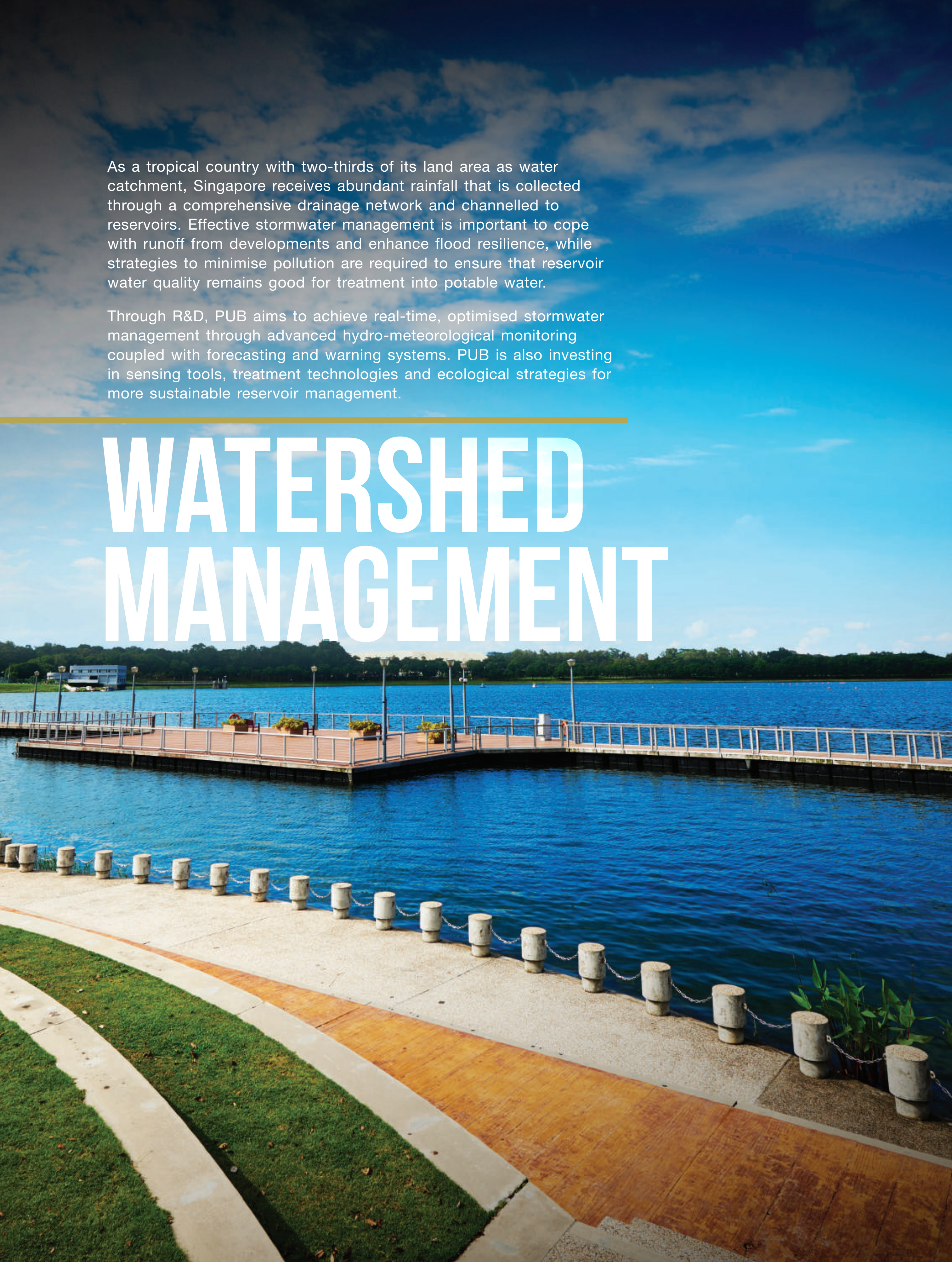
Lastly, any advice to students or young engineers who are keen to pursue a career in the water sector?

I certainly welcome the next generation to join our profession. If you are passionate about making the world a better place, and if you relish challenges that involve practical solutions grounded in science and engineering, a career in water is a job that will give you immense satisfaction. Not only will you use your knowledge to ensure the long-term survival of Singapore, the relevance and reach of your work will see you contributing towards global efforts in water and sanitation.

WATERSHED MANAGEMENT

As a tropical country with two-thirds of its land area as water catchment, Singapore receives abundant rainfall that is collected through a comprehensive drainage network and channelled to reservoirs. Effective stormwater management is important to cope with runoff from developments and enhance flood resilience, while strategies to minimise pollution are required to ensure that reservoir water quality remains good for treatment into potable water.

Through R&D, PUB aims to achieve real-time, optimised stormwater management through advanced hydro-meteorological monitoring coupled with forecasting and warning systems. PUB is also investing in sensing tools, treatment technologies and ecological strategies for more sustainable reservoir management.



Integrating stormwater detention and treatment features within a residential development

Piloting the large-scale integration of ABC Waters design features for sustainable stormwater management

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Singapore has moved from the traditional approach of building utilitarian concrete drains for efficient conveyance of stormwater, towards a more holistic and sustainable approach of managing stormwater runoff. Also known as the 'Active, Beautiful, Clean Waters (ABC Waters) Management Strategy', natural features are incorporated in the catchment to detain and treat runoff at source before it is discharged into the downstream public drains and waterways. This approach helps PUB to mitigate the impact of increased runoff and pollutant loading, caused by new developments and increased socio-economic activities.

To achieve effective runoff control, such ABC Waters design features should be widely proliferated throughout the catchments, starting at source in new developments, rather than being restricted to downstream waterbodies where runoff volume and pollutants would have accumulated in large amounts.

"ABC Waters design features are an effective means of controlling pollution at source with the use of natural purification processes," says Tan Nguan Sen, PUB's Chief Sustainability Officer. "To achieve catchment-wide implementation of design features in individual developments, the features must be considered in the early stages of planning and design of a development, not as an afterthought."

To pilot the first large-scale implementation of ABC Waters design features within a development, PUB collaborated with the Housing Development Board (HDB) to holistically integrate sustainable stormwater management strategies in a public housing development. Waterway Ridges (Fig. 1), a residential precinct located along the iconic Punggol Waterway, was selected as the demonstration site.

At every stage of the project, architects, engineers and landscape architects from PUB and HDB worked closely to coordinate the various aspects of the design, paying particular attention to the interfacing between drainage and landscape. As a result, a network of design features such as rain gardens, bioretention lawns and swales were well-integrated with the drainage system and the overall residential landscape. These features detain and treat the stormwater runoff from the housing estate before discharging the cleansed runoff into Punggol Waterway. A showcase rain garden (Fig. 2) was also constructed in the common green area.

FIG. 2: A showcase rain garden feature in the common green area

The successful completion of Waterway Ridges demonstrated that with integrated upstream planning, close design coordination and construction supervision, it is feasible to incorporate ABC Waters design features extensively and holistically in a housing development to improve stormwater quality and lower peak stormwater discharge rates, while creating aesthetically-pleasing features for residents to enjoy.

The positive results of this demonstration project will spur the proliferation of similarly designed developments throughout Singapore in the future. With two-thirds of Singapore's land area water catchment, this project is a significant milestone in improving urban surface runoff quality by catchment-wide implementation of ABC Waters design features.

FIG. 1: Project demonstration site at Waterway Ridges

Improving water quality at-source using in-stream wetlands

Study of prototype in-stream wetlands to improve the quality of dry-weather base flows in canals

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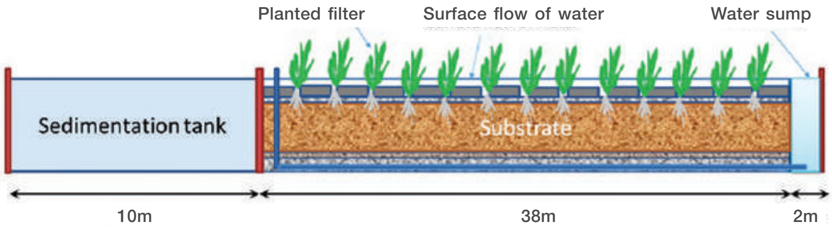

FIG. 1: Cross-section diagram of the wetland (water flows from left to right)

In land scarce and densely built-up Singapore, concrete drainage canals are often surrounded by developments. This poses challenges to the effective implementation of water cleansing features which are constructed adjacent to drainage canals, such as biofilters and constructed wetlands. These features typically require larger areas of land to improve the quality of storm water runoff from the urban landscape closer to source.

To mitigate this land constraint, a new approach in the form of an in-stream wetland was tested by the National University of Singapore, Deltares and Delft University of Technology.

"In this project, we placed a constructed wetland directly within an existing canal to study the treatment efficiency of the wetland on the base flow. We also investigated if the wetland led to any increase in flood risk during peak flow," said Ooi Seng Keat, principal investigator of the project.

To construct the wetland, laboratory experiments and computer simulations were carried out to provide recommendations and initial guidelines for the design. These guidelines were further validated with field data based on a pilot that was constructed and installed at the Zhenghua Road outlet drain.

The final wetland design consisted of a sedimentation tank upstream of the in-stream wetland's biofilter (Fig. 1). The sedimentation tank reduced the sediment load on the wetland, so the wetland could effectively treat the canal's base flow. To cater for suitable retention times for treatment, stop-logs were also installed upstream of the wetland to control water inflow. Plants with good treatment abilities, aesthetic value and minimal frictional resistance to water were selected for the wetland.

The wetland prototype was monitored for six months to assess its ability to improve base flow water quality. Water quality samples were taken at four locations across the sedimentation basin and wetland.

Results showed evidence of nutrient removal (of up to 50% of nitrate) by the wetland. The combination of the sedimentation basin and wetland was also effective in removing suspended sediments from the base flow.

However, due to challenging weather conditions, several plant species in the filter bed did not survive (Fig. 2). Some plants were uprooted during heavy storms and higher inflows, or deteriorated due to insufficient inflow. Both scenarios contributed to a lack of organic nutrient removal, measured in the form of total nitrogen and phosphorus.

"Overall, this study has demonstrated the potential of the in-stream wetland," said Ooi. "For such a system to be effective, it is important to ensure effective control of the inflow and an extended growing-in period with minimal stress to maximise the survival of plants species in heavy storms."

FIG. 2: Photos of the in-stream wetland from downstream looking upstream when constructed (left) and at the end of the study (right)

Managing microalgae growth with ultra-low frequency technology

Examining the efficacy of ultra-low frequency treatment system for algae control in Singapore's reservoirs

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FIG. 1: The ultra-low frequency (ULF) treatment system onboard a floating pontoon in Serangoon Reservoir

Microalgae grow rapidly when favourable conditions, such as warm and calm water, sufficient sunlight and nutrients, are present, and can lead to low levels of oxygen in water. When microalgae die, the decomposition process also consumes dissolved oxygen and releases nutrients back to the water. This decreases the dissolved oxygen levels in the water, and results in constant regeneration of microalgae under favourable conditions.

To control excessive microalgae growth in Singapore's freshwater reservoirs, PUB and Ecospec Global Technology (Ecospec) recently completed a research project to study the effectiveness of an ultra-low frequency (ULF) algae control unit (ACU) treatment system.

ULF technology uses an electromagnetic field or wave which has an ultra-low time-varying frequency range of 100 Hz to 2000 kHz. The ACU comprises of emitters and receivers which are energised by a power unit during operations. The ACU amplifies the ULF wave, creating a disinfection effect on bio-organisms that is similar to the avalanche current produced in fluorescent tubes.

This research was commissioned following a 2015 trial study where the ULF system demonstrated effective control of microalgae growth in a single pass confined tank treatment (control test). The ULF treatment did not result in the formation of disinfection by-products or have any ecotoxicity effects on aquatic ecology.

In this project, a 500 m^3/h ULF ACU treatment system, consisting of a power unit and the ACU, was mounted onto a floating pontoon in Serangoon Reservoir (Fig. 1). The ACU was installed along the pontoon pipeline, and reservoir water was continuously pumped through for exposure to the ULF (Fig. 2).

A series of microalgae treatment tests based on the chlorophyll-a content (a surrogate parameter for microalgae population) was carried out at various areas in Serangoon Reservoir to determine the immediate and 1-day residual microalgae treatment efficacy. The test results proved that effective treatment efficacy could be achieved with the ACU, with an average of 18% algae removal for immediate treatment and an average of 36% microalgae removal for the combined immediate and 1-day residual effect.

To further assess the residual effect in the longer term, mesocosm studies were also carried out. Reservoir water was collected before and after the single pass treatment and placed in mesocosms inside the reservoir. The conditions of the samples (e.g. water temperature and light conditions) were thus maintained in similar reservoir conditions. Chlorophyll-a content was observed to be consistently reduced over a period of 21 days after the single pass ACU treatment.

"Through this study, this mobile ULF technology-based algae control treatment system has proven to be suitable for application in waterways and reservoirs that are accessible and face issues with excessive algae growth. The system can help with algae control in localised areas," said Chew Hwee Hong, Founder and Managing Director at Ecospec.

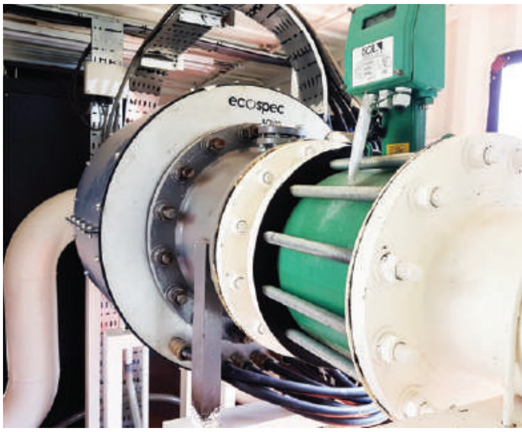

FIG. 2: Algae control unit (ACU) installed along the pipeline

PUB is committed to ensuring a safe and adequate supply of drinking water through the sustainable production of potable water from rainwater collected in catchments, seawater, and treated used water. The treatment process for these sources of water is not without challenges. PUB's goal is to achieve maximum recovery and consistently good water quality efficiently.

WATER TREATMENT, DESALINATION & REUSE

Improving the efficacy of treating recycled water with advanced oxidation

Pilot study on the efficacy of ultraviolet-based advanced oxidation in improving the resilience of the NEWater treatment

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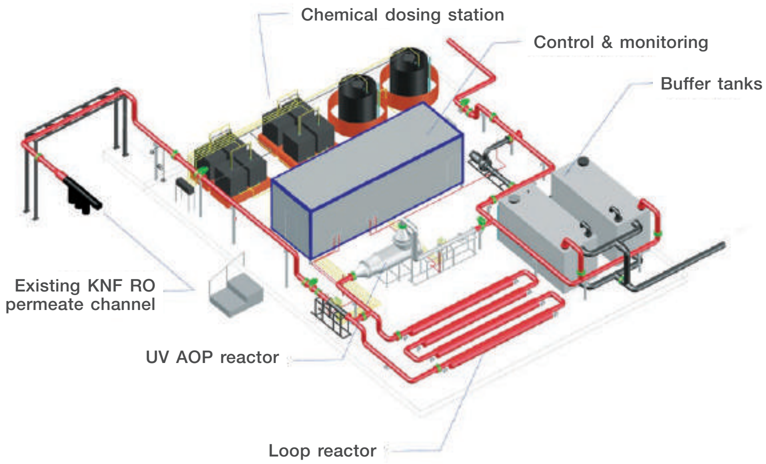

FIG. 1: The 1.7 mgd ultraviolet (UV)-based advanced oxidation process (AOP) pilot plant in Kranji NEWater Factory

NEWater, or recycled water, is one of Singapore's sources of water supply, meeting up to 40% of the country's current water demand. Although it is mainly for direct non-potable use, NEWater also supplements Singapore's potable water supply via reservoir recharge during dry months.

To ensure that recycled water meets international drinking water standards, an ultraviolet (UV)-based advanced oxidation process (AOP) is usually introduced after reverse osmosis to break down organic micropollutants and provide an additional protection barrier against pathogens. AOPs generate large quantities of the highly reactive hydroxyl radical, which destroy almost all organic molecules present in the water.

Hydrogen peroxide is commonly used to generate the hydroxyl radicals in UV-based AOPs. However, the use of hydrogen peroxide incurs significant chemical costs as it generates large amounts of residual peroxide that needs to be removed. If this is not done, residual peroxide may react with and cause the depletion of chlorine in the product water. Chlorine is an important disinfectant that prevents microbial growth in the water as it is transmitted along the distribution network. As such, alternative oxidants such as sodium hypochlorite are increasingly being used for the production of hydroxyl radicals.

To assess the effectiveness of UV-based AOP using sodium hypochlorite, Xylem Inc. (Xylem) is collaborating with PUB on a 1.7 mgd pilot plant at Kranji NEWater Factory (Fig. 1) involving the use of their Wedeco UV-AOP reactor.

The performance of AOPs will be assessed over a two-year period based on (a) the removal efficiency of a list of targeted compounds such as 1,4-dioxane and NDMA, and (b) the formation of any harmful oxidation by-products (OBP) such as trihalomethanes, which may result from chemical reactions between organic and inorganic matter in the water.

"This project investigates the replacement of hydrogen peroxide with sodium hypochlorite to potentially reduce treatment costs and chemical dosing, with the aim of making UV-based AOPs for water reuse more efficient and sustainable," said Jens Scheideler, Xylem's global AOP manager and project principal investigator.

Xylem will also attempt to optimise the UV and chemical dosage to achieve the required treatment efficacy while simultaneously minimising chemical and energy consumption of the treatment process. To do this, bench-scale experiments using a Collimated Beam Device (CBD) (Fig. 2) will be conducted. The CBD is a compact, table-top UV delivery system consisting of four UV low-pressure lamps radiating UV light at 254 nm, and will help to pre-determine the dose-response curves of various contaminants, water quality parameters and potential formation of OBPs prior to pilot-scale testing.

In addition, Xylem will identify the critical control points within the treatment process so that online sensors and controls can be installed during full-scale implementation to facilitate monitoring and operation of the system.

The eventual success of UV-based AOPs would increase the resilience of existing NEWater treatment processes and open up new opportunities for an expanded range of reuse applications.

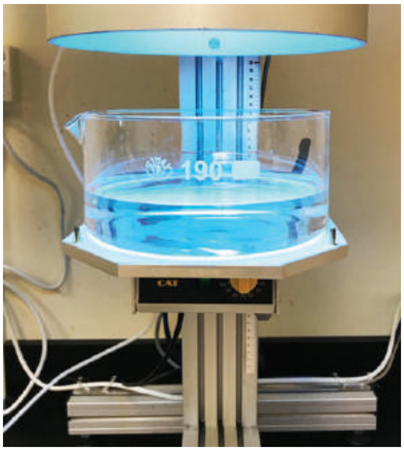

FIG. 2: UV irradiation of sample using the Collimated Beam Device (CBD)

Controlling biofouling in reverse osmosis

Pilot study uses new slime control agent and in-situ electrical impedance spectroscopy fouling sensor to control biofouling in reverse osmosis

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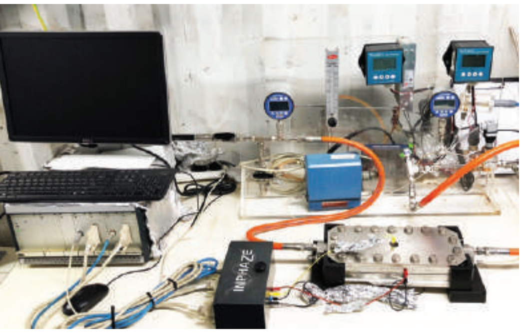

FIG. 1: Electrical Impedance Spectroscopy Fouling Monitor (EISFM) set-up at the pilot seawater reverse osmosis (SWRO) plant

Membrane fouling during the reverse osmosis process is a common challenge faced by water utilities. This happens when microorganisms in the feed water adhere and grow on the membrane surface as a concentrated layer of biofilm.

The biofilm clogs up the membrane, causing the differential pressure (ΔP) across the membrane surface to increase over time. Higher pressure is required to push the feed water through the membrane, resulting in increased energy consumption and production losses. To minimise this, the fouled membranes are frequently cleaned using chemicals, but this leads to the deterioration of the membranes over time.

Kurita Water Industries (Kurita) has developed a new slime control agent Kuriverter® IK-110 to tackle the issue of membrane biofouling in a more sustainable way.

“Unlike conventional biocide, which uses chemicals to kill microorganisms in the biofilm, IK-110’s antifouling effects are achieved by targeting the mechanism responsible for the microbial production of extracellular polymers, such that the biofilm ‘peels-off’ from the membrane surface gradually,” said Hideyuki Komori, principal investigator from Kurita. “Because cell death is not necessary, IK-110 is chemically milder than its contemporaries, though by no means less effective. This results in negligible impact on membrane integrity.”

To test the efficacy of IK-110 for large-scale seawater reverse osmosis (SWRO) plants, Kurita recently partnered with the Nanyang Environment & Water Research Institute - Singapore Membrane Technology Centre (NEWRI-SMTC) on a study involving a pilot SWRO plant at PUB’s R&D facility in Tuas.

The performance of the pilot plant’s two SWRO trains – one dosed with IK-110 and the other without – were compared in parallel (Fig. 1).

Over three consecutive tests, it was observed that the ΔP of the RO train with continuous dosing of IK-110 remained stable, while the other experienced a gradual increase over time (Fig. 2). This confirmed the effectiveness of IK-110 as a slime control agent to mitigate biofouling. The conclusion was further supported by membrane autopsy studies which showed lesser biofilm formation with IK-110.

The study also addressed an existing limitation in conventional fouling monitoring methods. While ΔP is a useful indicator of biofilm formation, the initial stages of the fouling process – where low levels of foulants do not result in significant pore blockage – may not reflect observable increases in ΔP. A parallel task in this study aimed to verify the capability of NEWRI-SMTC’s Electrical Impedance Spectroscopy Fouling Monitor (EISFM), a technology which monitors the conductance of the membrane’s diffusion polarisation layer (G_{DP}) in-situ to detect changes in the membrane’s surface layer as an indication of biofilm formation.

The trial study showed that an increase in G_{DP} was not matched by a corresponding increase in ΔP. The G_{DP} subsequently experienced a gradual drop from Day 45 onwards, indicating the onset of biofilm formation on the membrane surface. On the other hand, ΔP experienced a sudden increase only at Day 80. The results proved EISFM’s early warning capability.

Kurita and NEWRI-SMTC researchers are currently conducting further studies to investigate the use of EISFM to optimise the dosing regime of IK-110. Should the study be successful, EISFM can become an important fouling predictive tool, enabling operators to develop more effective cleaning regimes to prevent membrane biofouling.

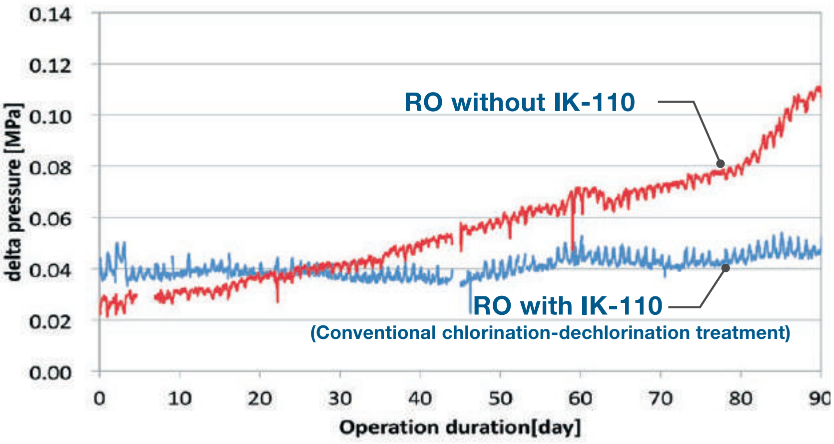

FIG. 2: Results of IK-110 efficacy study

Optimising water treatment processes to reduce wastage and production costs

Construction of portable plug-and-play modular pilot plants to optimise drinking water treatment processes

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The treatment of drinking water typically consists of the following processes - coagulation, flocculation, sedimentation, filtration and disinfection. To achieve better water quality, ozonation followed by biologically activated media filtration (BAF) is positioned right after filtration and before final disinfection. Taken as a system, these processes serve to remove pollutants, organic compounds and taste and odour substances.

While these processes are well established and applied in many water utilities, a key challenge lies in integrating and optimising them to achieve better quality water at reduced chemical consumption, lower waste generation, smaller energy footprint, and ultimately reduced production cost.

To achieve this, PUB has embarked on a project to construct portable plug-and-play modular drinking water treatment pilot plants at Choa Chu Kang Waterworks. These plants will allow PUB to conduct optimisation studies for individual treatment processes, and collectively as an integrated system. With individual capacities of 120 m^3/d, the modular pilot plants will consist of the following units – (a) coagulation, flocculation, sedimentation and filtration; (b) ozonation; (c) biologically activated media filtration; and (d) post-treatment (Fig. 1).

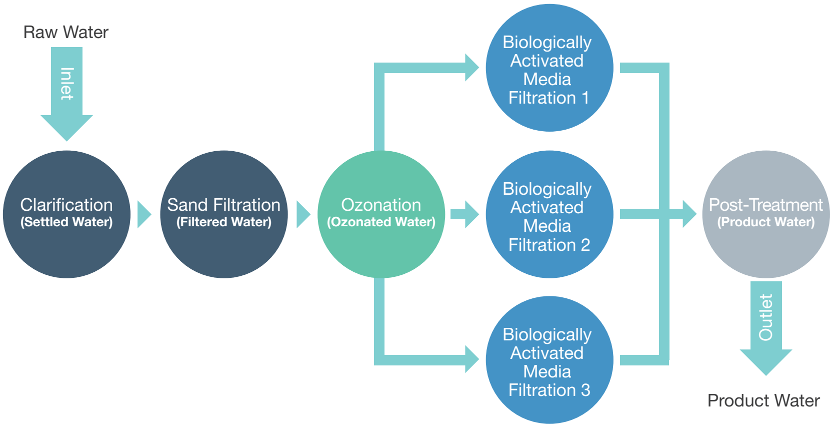

FIG. 1: Treatment process of the plug-and-play modular pilot plant

To optimise the coagulation, flocculation, sedimentation and filtration processes, inlet and outlet water quality parameters, such as total organic carbon, turbidity and pH, will be used to determine the optimal chemical dosages needed to form large and dense aggregates for easy and fast separation. Promising coagulants such as ferric chloride will be tested for their effectiveness and optimum dosage, based on parameters such as floc formation, product water quality and overall treatment cost.

During a typical ozonation process, up to 10% of the dosed ozone may not be consumed due to inefficient dissolution in water. This unconsumed ozone is released as off-gas which is then discharged to the ozone destruction unit. To optimise the ozonation process, two dosing approaches – single dosing and stepwise dosing – will be tested to identify a better way to improve the ozone transfer efficiency. They will be evaluated based on parameters such as ozone demand, removal efficiency of taste and odour compounds and targeted trace organic compounds, and reduced formation of disinfection by-products. PUB will also study the feasibility and cost-effectiveness of options to recycle the off-gas.

To optimise the BAF process, PUB will study the effectiveness of different media in removing organic compounds and their by-products that affect water quality (Fig. 2). Examples of media that will be evaluated include coal-based and coconut shell-based granular activated carbon. These various BAF media will also be tested to determine their respective ideal operating conditions.

“Based on our preliminary projection, we expect to achieve overall cost-savings of at least 10% with the successful optimisation of the individual unit operations”, said Rongjing Xie, principal investigator of the project. Upon completion of this pilot study, PUB will utilise the results to improve and optimise the operations of its full-scale water treatment plants.

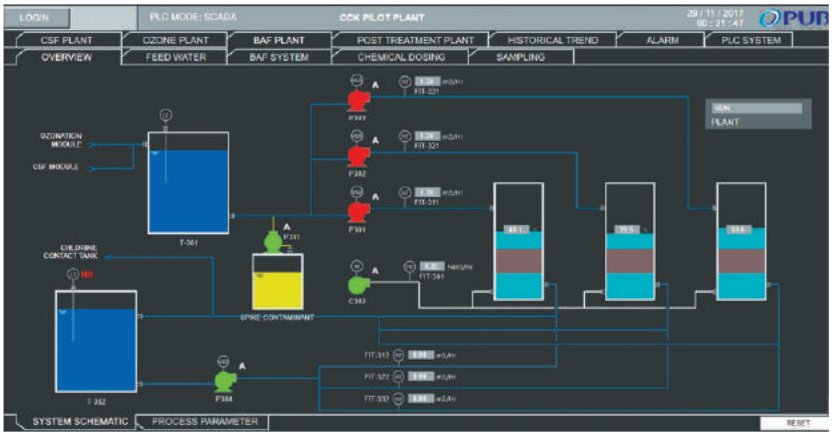

FIG. 2: A screenshot depicting the schematic flow of the BAF in the pilot plants

Besides discharging treated used water into the sea and relying on the natural hydrologic cycle to recycle the water, PUB also shortens the cycle by reclaiming used water and treating it to high standards for reuse.

To achieve this in the most efficient way possible, PUB is actively looking into treatment technologies that can minimise sludge formation and recover valuable resources from used water, while consistently producing high-grade effluent. Ultimately, PUB aims to achieve energy self-sufficient water reclamation plants to ensure long term sustainability in used water treatment.

USED WATER TREATMENT

Lowering energy requirements in biological nitrogen removal

Studying the effectiveness of the anaerobic ammonium oxidation process in lowering energy required to treat ammonia-rich dewatering centrate

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Biological nitrogen removal is an essential process in used water treatment to remove ammonia, a toxic pollutant that can cause eutrophication in natural water environments and pose potential hazard to human and animal health. Conventional biological nitrification, in which ammonia is removed through conversion to harmless nitrogen gas by the nitrification-denitrification process, makes up approximately 40% of total aeration energy required in used water treatment.

During the anaerobic sludge digestion and dewatering process in used water treatment, an ammonia-rich side-stream called dewatering centrate (DC) is produced. This side-stream is typically recycled and combined with used water influent to be treated at the water reclamation plant (WRP), increasing the plant nitrogen loading significantly.

To remove nitrogen from used water more effectively and reduce energy consumption from aeration, Meidensha Corporation (Meiden) and PUB collaborated on a study at the used water treatment demonstration plant located in Ulu Pandan WRP. Instead of recycling the ammonia-rich DC side-stream directly back to the influent, an anaerobic ammonium oxidation (Amox) treatment process was introduced to first reduce the nitrogen load in the DC stream (Fig. 1).

In the pre-treatment A-stage system phase, a biosorption tank and a clarifier was introduced to lower the total suspended solids (TSS) and chemical oxygen demand (COD) concentrations in the DC stream and improve the effectiveness of the Amox process.

The subsequent Amox process involves two steps in a single reactor. First, partial nitritation of ammonia into nitrite by ammonia oxidising bacteria (AOB) takes place under aerobic conditions. Then, anaerobic oxidation of the residual ammonia by nitrite into nitrogen gas was carried out by the Amox bacteria. As the latter process does not require aeration, less blower energy was consumed overall.

The Amox bacteria is commonly seen as red granules with higher density (Fig. 2). To ensure its healthy growth, and to control the growth rate of nitrite oxidising bacteria (NOB), the balance of aeration supply during the Amox process is important. Unlike Amox bacteria, NOB requires oxygen to convert nitrite to nitrate and has a growth rate that is 10 to 15 times faster than Amox bacteria. Too much oxygen can therefore result in the growth of the undesirable NOB over the Amox bacteria, which suppresses Amox activity.

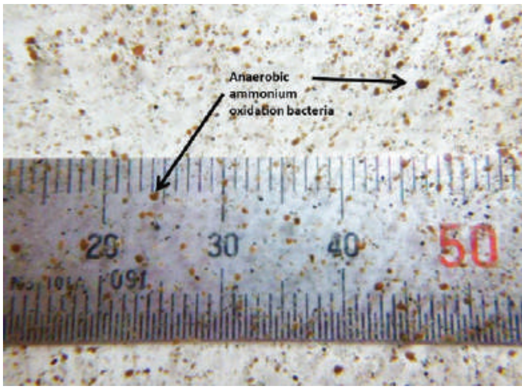

FIG. 2: Anaerobic ammonium oxidation (Amox) bacteria are commonly seen in the form of red granules

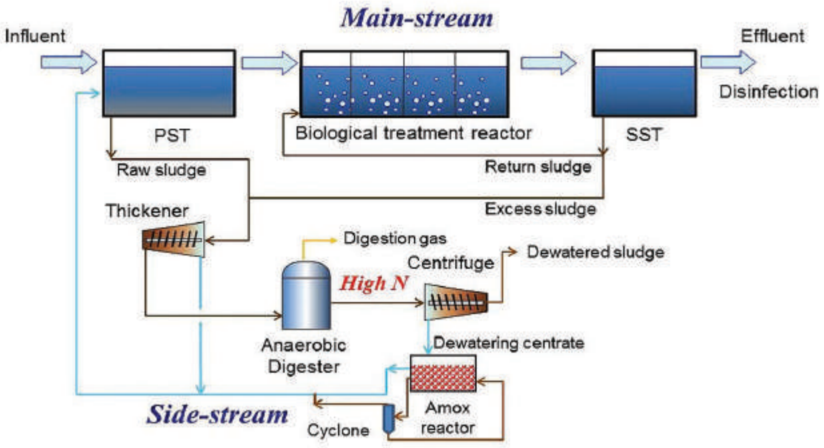

FIG. 1: Diagram showing the main-stream and side-stream treatment of used water

To provide for the best possible conditions for the growth of Amox bacteria over NOBs, the EssDe®, a patented surplus sludge separation technology, was employed to retain and enrich the slow growing Amox bacteria. A hydrocyclone was also introduced to separate the heavier Amox bacteria which was returned to the reactor to maintain the right quantity of Amox bacteria for optimum nitrogen removal. The lighter AOB and NOB were discharged.

"Amox was first successfully tested during a pilot study at Changi WRP in 2013 without the pre-treatment A-stage system. From this study at the used water treatment demonstration plant at Ulu Pandan, the Amox process coupled with A-stage as pre-treatment appears to be a viable alternate method to treat ammonia-rich DC with different influent characteristics with low aeration energy consumption," said Terutake Niwa, principal investigator of the study. "The results will have useful application in used water treatment in future."

Recycling industrial used water for industrial reuse

Study on Electrodialysis reversal (EDR) technology for recycling industrial used water

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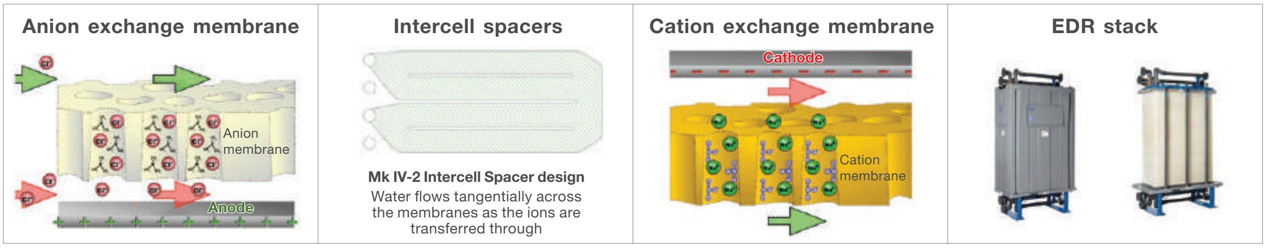

FIG. 1: Electrodialysis reversal (EDR) membrane, spacer and stack

Recycling industrial used water for industrial reuse is one way to meet the increasing water demand in Singapore. However, due to the complex nature of the pollutants present in industrial used water, recycling of industrial used water can be technically and economically challenging.

Currently, an industrial membrane bioreactor (MBR) in the Jurong Water Reclamation Plant (Jurong WRP) collects and treats industrial used water from the Jurong industrial estate. The MBR produces filtrate with conductivity of about 3,000 to 5,000 µS/cm and chemical oxygen demand (COD) of around 100 ppm. For this filtrate to be reused as high grade industrial water, it is necessary to reduce the conductivity to below 1,600 µS/cm. However, the high COD levels increases the fouling potential of the filtrate, limiting the use of reverse osmosis (RO) technology in industrial used water treatment. A process that could withstand high COD, and achieve significant conductivity reduction and high water recovery, was therefore needed.

In partnership with SUEZ, PUB embarked on a research project to study the use of EDR technology as an alternative to RO for treating industrial used water. EDR (Fig. 1) is an automatic self-cleaning technology that utilises ion movement to treat used water by means of an electrical driving force that reverses the polarity of the direct current voltage a few times per hour. The polarity reversal helps to detach the pollutants from the surface of the membranes accumulated during the previous cycle. The EDR performance was tested under real feed conditions to optimise and validate maintenance procedures to achieve stable long-term operations with minimum chemical cleaning.

"Due to its polarity reversal mechanism, EDR process application in municipal used water treatment is known for its robustness to fouling and scaling. This effectively reduces foulant accumulation on the membrane surface during continuous operation while simultaneously providing high water recovery," said Kia Kian Kee, principal investigator of the project.

A 50 m^3/day EDR pilot plant was installed and commissioned at Jurong WRP for a six-month trial. The pilot plant consists of 80 cell pairs (anion and cation ion exchange membranes separated by the spacer). A multi-media filter was installed to protect the EDR during process upsets at the MBR plant. Small doses of acid and antiscalant were added to inhibit inorganic scale formation caused by high concentration of phosphate and fluoride in the feed water.

The EDR pilot plant delivered stable and robust performance during the trial, successfully producing high quality product water with conductivity of 500-800 µS/cm (Fig. 2). Only minor increases in stack resistance and a slight drop in pressure was observed, while SUEZ's newly developed low resistance membranes needed cleaning only at the end of the six-month trial period. These demonstrated the stability of the EDR process even with high COD feed.

"Through this study, EDR has proved to be a promising technology to recover industrial used water. Moving forward, we will continue to work with PUB for process optimisation and eventually full-scale implementation," said Kee.

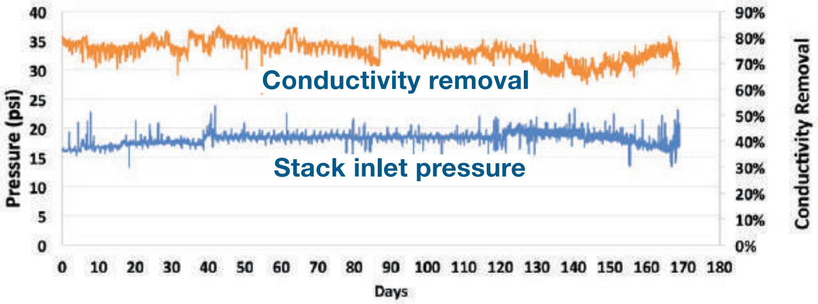

FIG. 2: EDR performance in operating pressure and conductivity removal

Microbial approach for removing phosphorous from used water

Study on the feasibility of enhanced biological phosphorus removal in high temperature regions via microbial monitoring and analysis

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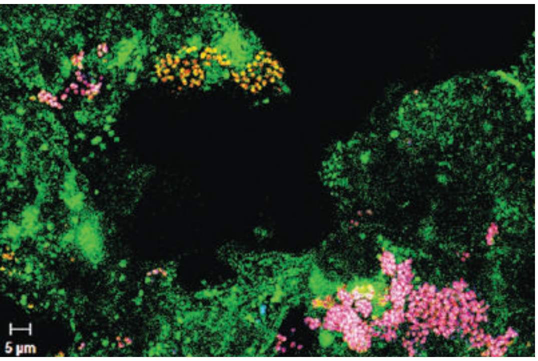

FIG. 1: Fluorescence in-situ hybridisation (FISH) images showing presence of polyphosphate accumulating bacteria (indicated in orange and magenta) in the activated sludge from Ulu Pandan Water Reclamation Plant (WRP)

Phosphorus is an essential element for all life forms, although its release into water environments can stimulate algal blooms. Enhanced biological phosphorus removal (EBPR) is a method that achieves cost-effective and sustainable removal of phosphorus from used water. Polyphosphate accumulating organisms (PAOs) store the element in the form of polyphosphate granules inside their cells, which requires a cycling between anaerobic and anoxic-aerobic conditions. However, EBPR has long been considered unstable in high temperature regions such as Singapore, because glycogen accumulating organisms (GAOs) will outcompete PAOs for organic carbon substrate.

PUB and the Singapore Centre for Environmental Life Sciences Engineering (SCELSE), a Research Centre of Excellence hosted by Nanyang Technological University (NTU) and the National University of Singapore (NUS), have been investigating the viability of EBPR in tropical climate conditions.

"The utilisation of a holistic research approach, where full-scale monitoring studies are supplemented with lab-scale experiments, allows us to establish the feasibility of performing EBPR at high temperatures," said Stefan Wuertz, principal investigator of the project.

A two-year monitoring campaign of the process performance, which included weekly DNA sequencing of the bacterial community, was conducted at Ulu Pandan Water Reclamation Plant (WRP) where phosphorus was being removed without a planned EBPR process. The study showed that an active community of PAOs (Fig.1) co-existed with GAOs, thus supporting the viability of tropical EBPR. "By further manipulating competition dynamics under different operational parameters, we observed that the PAOs increase in abundance and enhanced the extent of phosphorus removal," (Fig. 2) said Ying Yu Law, a lead postdoctoral scientist on the team.

Subsequent lab-scale investigations uncovered the predominance of non-denitrifying PAOs in the plant. These microbes were able to recognise the anoxic compartment as an anaerobic stage, making EBPR achievable under anoxic-aerobic treatment conditions. These findings overturned conventional thinking and have significant implications for the future design and operation of tropical EBPR plants.

As carbon source type is a key factor governing the stability of the EBPR process, the team is presently investigating the relationship between carbon source usage and PAO community composition across three WRPs in Singapore.

"We are systematically analysing and interpreting a large volume of operational and microbial community data to uncover more insights into EBPR and ultimately contribute to more reliable biological phosphorus removal from used water in warm climates," said Guanglei Qiu, a postdoctoral fellow on the team.

Complementing the field investigations, lab-scale systems are being operated to enrich the key EBPR microorganisms for further genetic and physiological studies. When the recovery of the complete genome of the PAO species enriched at high temperature is completed, it will provide new genetic and metabolic insights on how these microorganisms can potentially be manipulated to perform optimal EBPR in tropical WRPs.

"The new DNA sequencing technologies will enable us to gain insight into the microbiological functions," said Rohan Williams, a computational biologist who leads that component of the study.

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

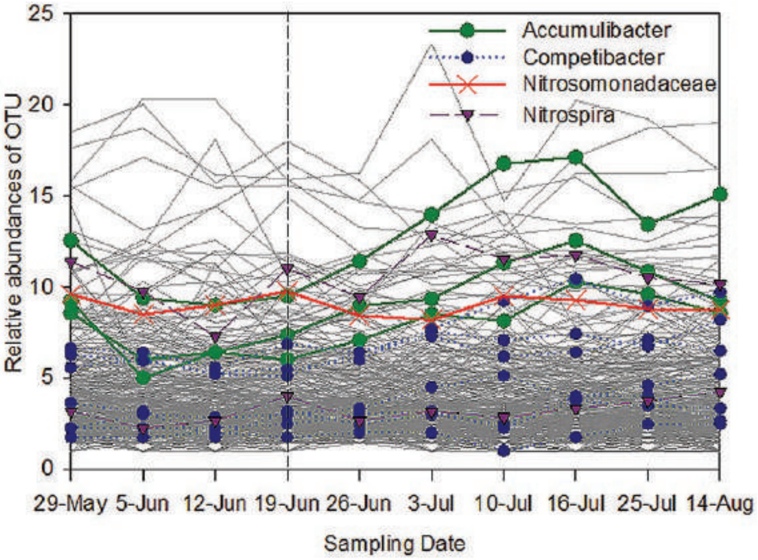

FIG. 2: Low dissolved oxygen levels increased the relative abundance of the PAO known as *Candidatus* Accumulibacter.

To safeguard water quality, PUB strives to maintain a comprehensive, accurate and timely understanding of the contaminants that may potentially be present in our water systems. Through the development and implementation of rapid, online in-situ sensors as well as sensitive, automated lab-based methods, PUB aims to achieve holistic and real-time water quality monitoring of contaminants that are known or of emerging concern.

WATER QUALITY & SECURITY

Clean water requires a clear understanding

Ecological system analysis of Pandan Reservoir identifies key processes that impact water quality for more targeted and effective intervention

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In water systems such as reservoirs, effective measures to maintain or improve water quality are important to ensure that downstream treatment processes are not compromised. The wide array of measures available can, however, be a challenge. As each reservoir has a unique set of physical, chemical and ecological processes that influence water quality, measures that prove effective in one reservoir may prove ineffective in another.

To support water managers in the Netherlands in determining which management approach is best suited for particular water systems, the ecological system analysis was developed. This methodology helps to identify key processes that influence water quality (Fig. 1), allowing water managers to assess the effectiveness of intervention measures . To evaluate the applicability of system analysis in local reservoirs, PUB is collaborating with engineering consultancy Witteveen+Bos South East Asia on a project involving Pandan Reservoir as the trial site (Fig. 2).

FIG. 2: A field visit to Pandan Reservoir to collect water samples

FIG. 1: Framework of 9 ecological key factors that determine reservoir water quality

1 – productivity of the water (biological productivity related to nutrient dynamic in the water column)
2 – light climate;
3 – productivity of the sediments (biological productivity related to nutrient content of the sediments);
4 – habitat suitability;
5 – connectivity (possibilities for migration of biota to and from the reservoir);
6 – disturbance/removal;
7 – organic loading;
8 – toxicity; and
9 – context/experience (consideration of measures in socio-economic environment)

"System analysis is about ascertaining the key factors and processes that contribute to water quality in a particular environment," said Guus Kruitwagen, principal investigator of the project.

This begins with an analysis of the observed water quality. A hypothetical basis that aims to explain the observed qualities is developed, and then digitally simulated to obtain a model of the reservoir water quality. System analysis is carried out by comparing the observed water quality data with the model predictions, and discrepancies indicate key processes that may not have been considered in the formulation of the hypothesis. Once the key processes have been identified, the verified model can be used to predict the way water quality would change in response to potential measures and management strategies. "The key is to keep an open view beyond the boundaries of conventional thinking and be prepared to take several steps backwards to see the bigger picture," said Kruitwagen.

The system analysis of Pandan Reservoir revealed clear connections between implemented reservoir management practices, the observed water quality, and physical characteristics of the reservoir. The findings show that sediments play a dominant role in influencing water quality, while incoming water flows assume a much smaller role than expected. This sheds light on how the measures implemented at Pandan Reservoir can be improved for more effective water quality management.

Similar interventions have proven effective in the Netherlands where reservoir management strategies informed by system analysis have resulted in the prevention of algal blooms. If successfully implemented in Singapore, this method has the potential to facilitate the development of targeted intervention approaches for more effective water quality management in our local reservoirs.

Prioritising research on contaminants of emerging concern

Developing a decision-making framework for the prioritisation of research on contaminants of emerging concern

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Contaminants of emerging concern (CECs) are substances, typically detected at concentrations ranging between 1 ng/L and 1 µg/L, which researchers are beginning to suspect may cause harm. In general, there are three main reasons that drive interest in CECs: synthesis of new chemicals, changes in the use of chemicals (which may lead to new exposure routes such as via drinking water) and improved detection technologies that can detect contaminants at ever lower concentrations.

Due to their large number (in the order of thousands) and diversity, little is known about the health effects of many CECs. While used water or drinking water treatment processes are capable of removing most contaminants from our water systems, additional treatment may be required to better address certain classes of contaminants that can pose risks to public health or environmental organisms. Because these treatment processes often involve advanced technology, they are likely to be costly and more energy-intensive. Decisions to implement these processes must therefore hinge on the actual risk that CECs pose for water treatment to remain adequate and economically viable.

As there are limitations in resources and a large number of possible contaminants, only CECs suspected to have a high level of risk should be prioritised for investigation. This requires a rigorous decision-making framework to help regulators determine which contaminants warrant a full risk assessment.

PUB is working with the Global Water Research Coalition and the University of New South Wales (UNSW) to develop a practical framework for CEC research prioritisation. Stuart Khan at UNSW, who is the principal investigator for the project, said, “Such a framework will assist water utilities in identifying appropriate criteria for prioritisation, techniques for ‘weighting’ these criteria, techniques for assessing options against the criteria, and techniques for drawing conclusions on research prioritisation”. Examples of such criteria include whether or not the contaminant is known or suspected to cause acute or chronic health risks, and the availability of information regarding the efficiency of its removal during the water treatment process. The framework would offer a number of advantages to utilities, such as an improved basis for research priority decision-making, better accountability to stakeholders, and more informed policy-making.

In order to make the framework accessible, Khan’s team is also working on developing it as an online resource. “The basic tool that we have developed is built on an established methodology for multi-criteria decision analysis,” he said. “The tool is coded into a Bayesian Network, enabling us to incorporate levels of uncertainty in the ways that CECs are classified.”

This project was initiated following a survey of water industry stakeholders to understand their current practices, criteria and requirements in the screening of CECs. Based on the responses received from research organisations, drinking water utilities and private companies worldwide, majority of respondents appear to rely on an informal prioritisation framework at best (Fig. 1). The results collectively point to the need for a more systematic framework for improved decision-making.

“We anticipate that a more generally applicable and systematic framework will lead to improved prioritisation of CEC research, thus increasing the value of research that subsequently takes place,” said Khan.

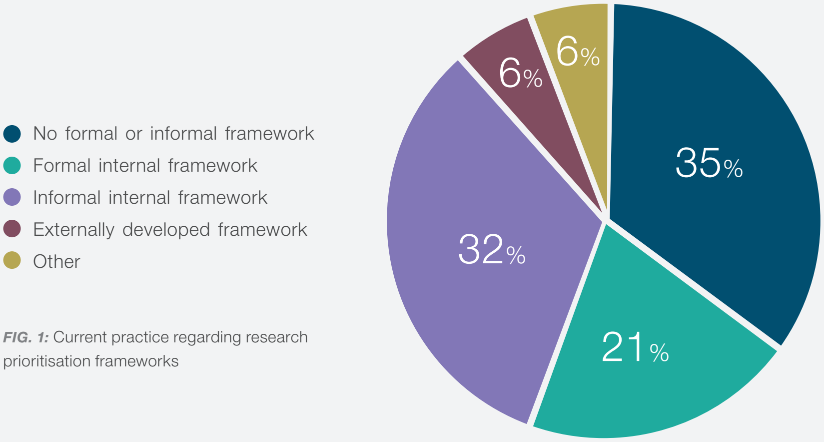

FIG. 1: Current practice regarding research prioritisation frameworks

Using DNA-based methods for freshwater biomonitoring in Singapore

Developing methods to replace traditional morphological tools with DNA-based approaches for biomonitoring of reservoirs and waterways

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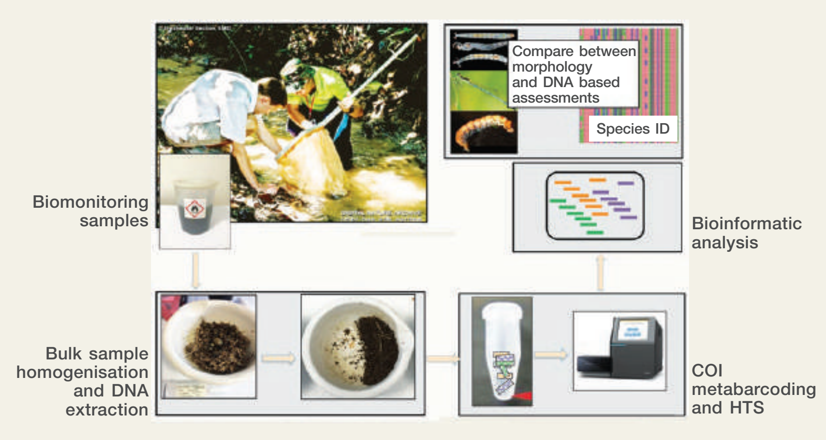

FIG. 1: Workflow of DNA-based approach to biomonitoring

Biomonitoring, or the use of ecological parameters as indicators of environmental water quality, is one way to monitor the health of Singapore's reservoirs and waterways. This is achieved by analysing the populations of in-situ macroinvertebrates which are indicative of water quality. Current methods of identification and quantification rely on visual analysis of macroinvertebrate morphology. This is time-consuming, costly, and has limited taxonomic precision given that identification are restricted to the order- or family-level. This inability to distinguish between species of the same family or order affects the effectiveness of current methods, because different species belonging to the same group can have very different water quality requirements.

An alternative to morphology, DNA-based biomonitoring has been gaining popularity around the world. DNA-based methods are attractive because they can provide precise, species-level information on a larger range of indicator organisms. In addition, the availability of high-throughput sequencing (HTS) is now rendering DNA sequencing cost-effective.

To test the performance of DNA-based sequencing approaches on local samples *vis-à-vis* traditional morphological techniques, a team of researchers led by Rudolf Meier from the National University of Singapore is collaborating with PUB to carry out a comparative study using both methods on the same samples. The DNA sequencing workflow involves DNA extraction of bulk samples that have been homogenised (Fig. 1), followed by amplification and sequencing of "DNA barcoding" genes such as cytochrome c oxidase subunit I (COI), which have been shown to be particularly useful for species identification. This mass amplification of DNA barcodes from environmental samples is known as metabarcoding.

Bioinformatic analysis of the barcode data revealed DNA signals for more than 500 species across just ten samples. The results of the DNA-based analysis were largely congruent with the findings based on morphology (Fig. 2), affirming the suitability of COI barcodes for sample analysis. Furthermore, the approach offered much better taxonomic resolution – while most macroinvertebrate groups were detected by both techniques, the DNA-based approach was able to provide species-level information, which will allow for more meaningful water quality analysis in the future.

Based on the results obtained, researchers are presently generating a comprehensive COI barcode database of all major aquatic invertebrate groups living in local freshwater habitats. "Successful identification based on DNA barcodes is similar to the identification of individuals via fingerprints," explained Meier. "While the quantity of fingerprints from a particular site yields information on the number of persons present, one needs a fingerprint database where the prints are associated with names to also know who is present."

The few invertebrate groups that were detected by the morphological approach but not by DNA methods (those indicated in red in Fig. 2) are likely to be species that have not been included in this database. A sizable number of groups were also exclusively detected by DNA methods (those indicated in purple in Fig. 2).

Moving forward, the project team will be working on expanding the barcode database and optimising the sampling workflows to make DNA-based assessments operational for routine biomonitoring.

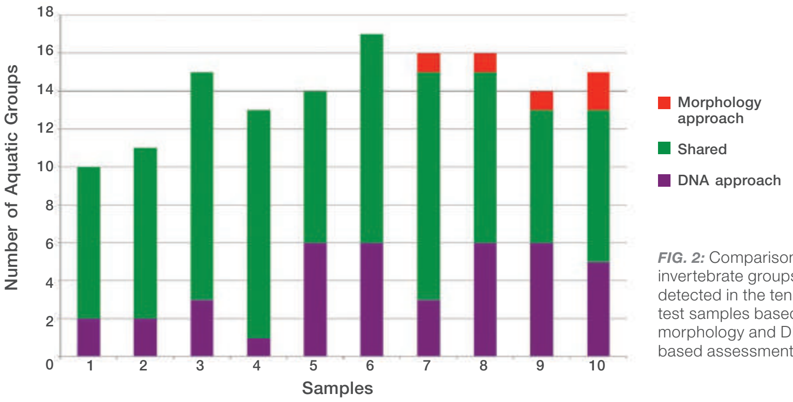

FIG. 2: Comparison of invertebrate groups detected in the ten test samples based on morphology and DNA-based assessments

As Singapore expands its water infrastructure to meet increasing water demand, PUB faces the challenge of extending the water supply and used water networks within an already congested underground environment, while maintaining the conditions of the current networks.

To maintain service standards efficiently, PUB will leverage technology to provide remote monitoring of water quality and network pressure, advanced leak detection and diagnostic forecasting of asset failure. PUB also aims to encourage water conservation by providing more accessible and granular consumption data to customers through smart metering and water-saving devices.

NETWORK MANAGEMENT & WATER CONSERVATION

Real-time surface surveillance of sewers using video analytics

Demonstrating the feasibility of using video analytics for early detection of potential threats to the Deep Tunnel Sewerage System

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In Singapore, used water from the northern and eastern part of the island is currently conveyed via deep tunnels to the Changi Water Reclamation Plant (Changi WRP) for treatment. The treated water is then either discharged to the sea or further purified into NEWater. Known as the Deep Tunnel Sewerage System (DTSS), it enables the large-scale collection and treatment of used water for recycling, ensuring the sustainability of NEWater. Phase 1 was completed in 2008, and Phase 2, which will extend the system to cover western Singapore, is expected to complete by 2025.

With an estimated lifespan of a hundred years, the 48-km long deep sewer tunnel for DTSS Phase 1 was laid at varying depths below the surface. As it cannot be seen from the surface, it could be damaged by construction activities such as piling, excavation or construction of retaining walls. Such damage causes disruptions to PUB's operations, and may require complex rehabilitation processes to repair the sewers.

Presently, PUB carries out routine surveillance, deploying physical patrols to check for unauthorised construction activities above the DTSS alignment. This method is time consuming, labour intensive, and does not provide real-time updates on site conditions.

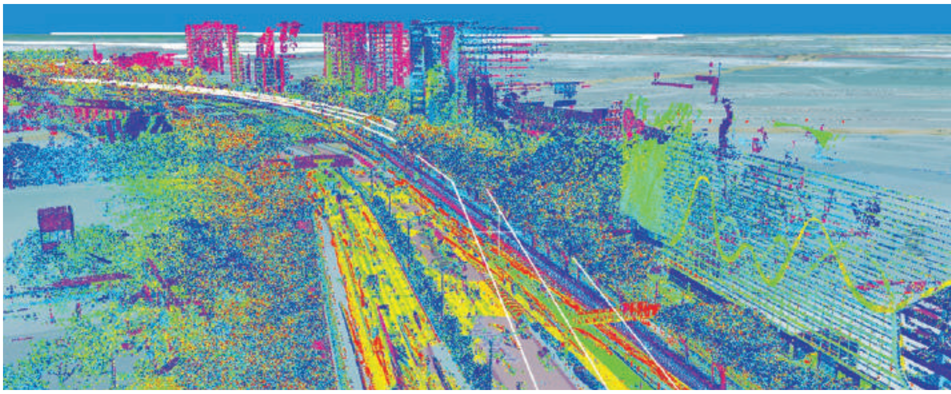

FIG. 2: DTSS coordinates were plotted on Light Detection and Ranging (LIDAR) software to pinpoint positions of the underground DTSS pipelines on surface terrain, as represented by the white lines

PUB and ZWEEC Analytics (ZWEEC) have embarked on a study to explore the feasibility of using video analytics to provide round-the-clock and automated surveillance of surface activities above the DTSS alignment (Fig. 1).

To do this, ZWEEC installed close-circuit televisions (CCTVs) at strategic points along the DTSS alignment. By geo-referencing a ground Light Detection and Ranging (LIDAR) scan (Fig. 2) with position data from a Global Navigation Satellite System, ZWEEC performed a desktop virtual survey to determine the number and optimal placement of CCTVs required to achieve full coverage of surface activities along the DTSS.

To assess the performance of the video analytics, images and videos of equipment commonly used in ground excavation works were first captured at various roads and construction sites. These were then classified according to type, tagged accordingly, and fed into ZWEEC's image processing engine. Video footages captured by the CCTVs during trial surveillance were then automatically compared against the digital reference library for image matching and identification. Results showed that the video analytics displayed a high level of accuracy and was able to provide near real-time detection and warning of potential disturbance to the DTSS caused by surface activities.

Summarising the benefits of the project, Koh See Kiat, principal investigator of the project, said, "We successfully demonstrated the feasibility of using video analytics to provide round-the-clock surveillance of surface activities along the DTSS alignment. Through optimised placement of CCTVs, the use of intelligent video analytics and the transmission of alerts in real time, the system is able to provide PUB with the ability to detect and identify possible surface threats, so that prompt and timely action can be taken."

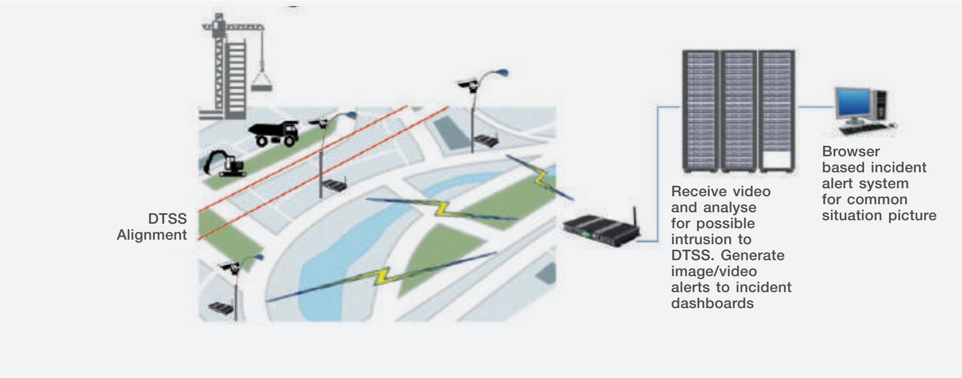

FIG. 1: Concept of operations for surface monitoring along Deep Tunnel Sewerage System (DTSS) alignment

Pushing the limits of water closets

Designing a water closet that can reduce the amount of water used for flushing

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FIG. 1: Modified flush toilet with two compartments of use

Over the years, per capita domestic water consumption in Singapore has fallen to 143 L per day. One major contributor of domestic water consumption is the water closets in homes and commercial premises. To further lower the per capita water consumption, PUB is collaborating with Rigel to push the limits of existing water-efficient water closets.

A key target of the project is to lower the current reduced-flush volume from 2.5 L to as little as 0.5 L – a significant 80% decrease in water usage. Water closets are designed with an S-shaped trap that is filled with water, forming a water seal which prevents odour from escaping through the sanitary pipeline into the homes. Because both liquid and solid waste enter the same trap, the trap is designed with a capacity that is large enough to accommodate and flush out solid waste in every use, regardless of the type of waste that actually enters the trap.

"Imagine the amount of water that is wasted with every flush of liquid waste as a result of the conventional toilet bowl design" said Wee Mun Wang, mechanical engineering manager of Rigel. "From the consumer's point of view, if the toilet design can be adapted to minimise such wastage, it could help consumers save on their water bills."

To address this, the team experimented with various design concepts, eventually focusing on a concept that separates the water closet into two compartments depending on type of waste (Fig. 1). This design is targeted at reducing water consumption during flushing in the context of male usage.

Much like a water closet integrated with a urinal bowl, the prototype design aims to divert liquid waste into a separate trapway or urinal bowl. After urination, pressured water from the supply network is released onto the interior surface of the urinal bowl via a spreader (Fig. 2), efficiently cleansing the bowl surface of liquid waste with as little as 0.5 L of water. The slanted angle of the urinal bowl is intended to create a bigger area for standing urination.

The team will be testing the prototype design against international water closet standards to ensure a good flushing performance. "Should this design prove workable, it will redefine toilet designs at home and may open doors to other forms of design that facilitate water conservation," said principal investigator Yong Chien Chan from Rigel.

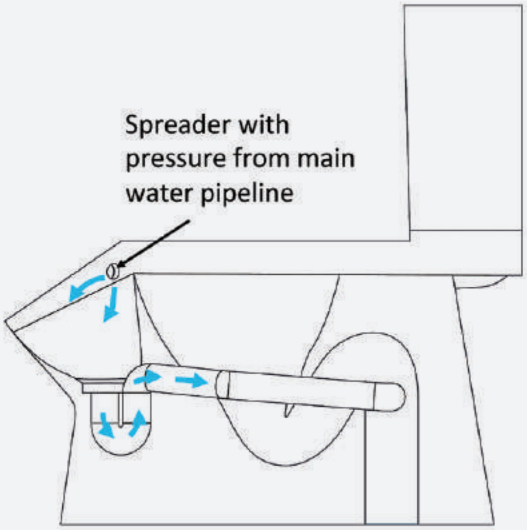

FIG. 2: The spreader uses the water pressure from the network to cleanse the interior of the urinal bowl

Smart metering for utilities

Developing integrated smart metering solutions to enable remote reading of utilities and provide timely consumption feedback to consumers

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In Singapore, town gas, water and most electricity meters are manually read for billing purposes. To provide more timely electricity consumption feedback, the government has rolled out smart electricity meters for business consumers.

In line with Singapore's smart nation initiative, the Energy Market Authority (EMA), PUB and SP Group co-launched an initiative to explore integrated meter reading solutions. A joint Call-For-Proposal (CFP) was launched to solicit technical solutions which leverage SP Group's existing wireless platform operated by Silver Springs Networks. In addition, the CFP also crowdsourced for ideas such as design features and functionalities, which could be incorporated by SP Group in the mobile application, and would enable consumers to access their consumption data easily.

In the third quarter of 2018, the technical solutions which were proposed and lab-tested by Mirai Electronics, TCAM Technology and ZH Technologies International will be deployed to a small group of residential and commercial premises as part of a pilot to assess their performance under actual conditions.

For the mobile application, EMA, PUB and SP Group received many good ideas for features such as utilities consumption comparison, notification functions and bill display and payment (Fig. 1). SP Group has adopted some of these ideas in development of the integrated mobile application for the three utility services. The mobile application will be tested as part of the pilot.

This digitised and integrated metering platform for all utilities will enable streamlining of operations among agencies. Regarding the impact on end users, PUB officer Lim Wee Beng said, "a digitised metering platform with more granular and timely consumption data will empower consumers to better manage their utilities consumption."

Your water usage is 43% less than last month

FIG. 1: Examples of mobile application interfaces designed to facilitate the monitoring and analysis of utilities consumption

Critical mechanical and electrical infrastructure supports PUB’s extensive networks and keeps the treatment systems running. As water infrastructure growth keeps pace with increasing water demand, PUB looks to better manage its expanding range of assets with advanced technologies that can provide accurate condition monitoring, predictive diagnostics and effective maintenance.

In turn, the digitisation and automation of PUB's operating environment will empower the workforce to better cope and even outperform convention. PUB will ride the digital wave to build a resilient and “smart” operating environment that is future-ready.

INTELLIGENT CONTROL SYSTEMS

Use of remote sensing techniques to monitor algal blooms

Assessing the applicability of remote sensing data from satellite images to improve water quality monitoring in Singapore waterbodies

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One of the major threats to the operation of desalination plants is the occurrence of harmful algal blooms (HABs) in seawater. Algal blooms can produce high particulate biomass and extracellular products that clog filters and foul membranes. Some HAB species also produce toxins, as well as taste and odour compounds that can affect the safety of drinking water. HABs have been occurring increasingly in Singapore coastal waters in recent years, evidenced in part by fish kill events in the Johor Straits (Fig. 1).

“In many regions, remote sensing using satellite images has become an important tool to monitor and predict the onset, location, and transport of HABs," explains Donald Anderson, Senior Scientist at Woods Hole Oceanographic Institution and principal investigator of a recent project to evaluate these tools for PUB. “But for Singapore, it has not been clear whether remote sensing would provide useful data."

Potential issues with cloud cover, spatial resolution, and image availability from open-source satellite platforms have traditionally limited the effective use of remote sensing tools in Singapore. The project therefore aimed to identify suitable satellite images and computer algorithms that could assist PUB in monitoring Singapore’s waterbodies, validate these images against measured field data, and tune the algorithms to overcome problems associated with cloud cover, haze and sun glint.

Results from the project demonstrated that current and next-generation satellites can provide useful information for monitoring water quality. For example, the availability of 10-metre resolution satellite data taken approximately every five days allowed PUB to “look between” the clouds even for small reservoirs (Fig. 2). Recently available ocean colour data from newer satellites such as the Sentinel-3B by the European Space Agency also enhanced PUB’s ability to monitor its coastal waters as the data can readily separate sediment plumes from potentially harmful algal blooms.

Another significant project outcome was the demonstration that freely-available satellite data can be processed in near real-time using open-source software, enabling PUB to integrate these methods into existing monitoring efforts. While standard global algorithms for parameters such as chlorophyll and total suspended solids performed reasonably well, the project demonstrated that locally tuned algorithms, developed using field data from Singapore waterbodies, can greatly improve the monitoring performance.

By enhancing PUB’s existing monitoring programme with the latest satellite capabilities, the project demonstrated the potential for an integrated observation system that provides spatial and temporal information on both unusual bloom events and long-term trends in Singapore waterbodies.

These research findings open up future research opportunities to link these observations to hydrodynamic models for bloom transport and landfall forecasts, which would then provide Singapore with a state-of-the-art predictive capability to manage potential impacts to desalination and drinking water systems as well as broad applicability to water quality monitoring.

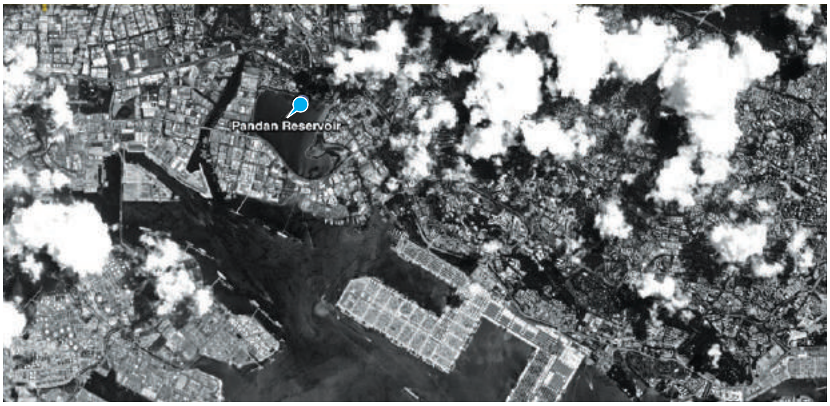

FIG. 2: With a 10-metre resolution satellite image, even though clouds are present it is possible to zoom in on individual reservoirs and retrieve data, such as Pandan Reservoir (labelled with a blue “pin” in the software).

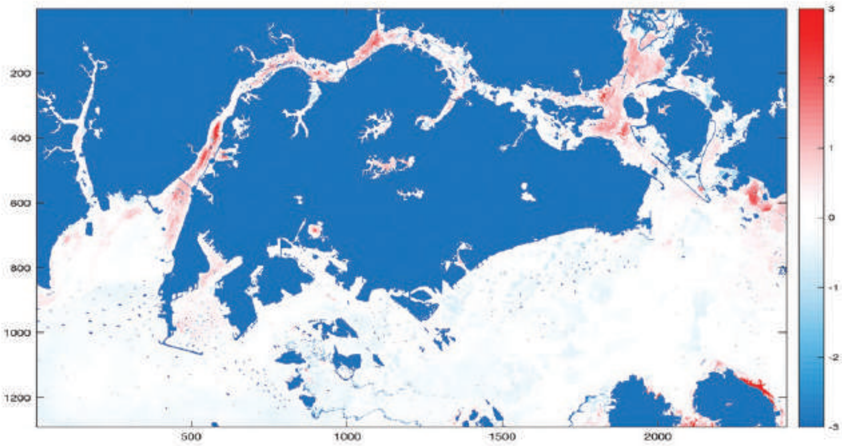

FIG. 1: High resolution time series imagery of Singapore waters can be used to create anomaly maps showing where blooms have occurred. In this image taken in February 2017 when there were documented blooms and fish kills, chlorophyll anomalies (red) appear throughout the Johor Straits.

Using big data and machine intelligence for water system protection

Detecting cyber-attacks and hidden faults in control systems via operational data anomalies

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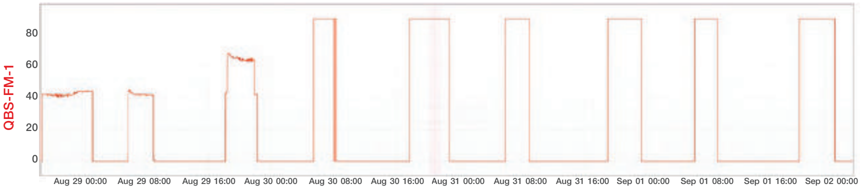

FIG. 1: Screenshot showing the detection of an abnormal process behaviour on the ICS^2 OnGuard system

Instrumentation and control systems such as the Supervisory Control and Data Acquisition (SCADA) system and online sensors have helped PUB reduce reliance on manual labour, minimise human errors in its operations and improve overall operational efficiencies.

However, there are challenges associated with the use of such automation systems. For example, SCADA systems are vulnerable to cyber threats; failure of unmanned online sensors may go undetected; and operational anomalies caused by equipment or process failures may not be easily detected and rectified. If left unaddressed, they can cause supply disruptions or, in more severe cases, shutdown of the entire water supply network.

PUB recently collaborated with Athena Dynamics to study the use of the ICS^2 OnGuard system to monitor and detect anomalous behaviour in its water supply network. The system was installed and trialled at PUB's Water Supply Control Centre (WSCC), which receives data from network installations across Singapore.

"At the core of this technology is a big-data analysis engine that utilises unique machine-learning algorithms to detect anomalies resulting from technical failures or cyber-attacks," said Sagi Gootman, ICS^2 project manager and principal investigator of the project. "Onguard creates an operational baseline and provides an alert when an unexpected disruption is encountered."

Designed to operate in a non-intrusive and passive manner, OnGuard monitors behaviour patterns by extracting data from historical databases while not interfering with the critical operational system of the network. It is also capable of monitoring multiple systems from different equipment manufacturers and identifying correlations in behaviour across these different devices and control systems.

When anomalies are detected, OnGuard is equipped with forensic tools that can assist in understanding the source and cause of the threat, as well as the impact on the specific physical processes that are affected.

Results obtained during the ten-month trial period were positive.

OnGuard was able to detect anomalies that would normally not be picked up as they occur within the SCADA system thresholds. By simply running in the background, OnGuard was also able to self-learn the operational baseline and carry out correlations in behaviour patterns without explicit data inputs from PUB. In addition, OnGuard demonstrated its ability to monitor and learn WSCC's processes even as its behaviour patterns change due to maintenance or process improvements.

When deviations due to sensor or equipment failures were detected (Fig. 1), OnGuard sent out timely alerts to PUB, allowing the operations team to promptly investigate the fault and carry out rectification. OnGuard was also able to detect performance variation when simulated cyber-attacks were carried out (Fig. 2).

"The project successfully demonstrated the ICS^2 OnGuard system's ability to provide timely and accurate warnings on abnormal sensor behaviour and process anomalies, thereby allowing PUB to carry out prompt rectification and reduce system downtime," said Sagi.

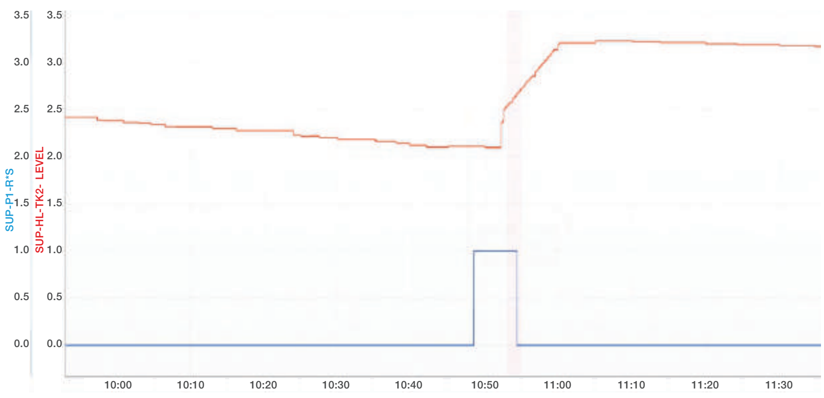

FIG. 2: Detection of variation in behaviour pattern due to simulated cyber-attack

Detection and containment of pollution in canals

Pollution detection and containment system detects and contains polluted inflows in concrete drains during dry weather flow conditions

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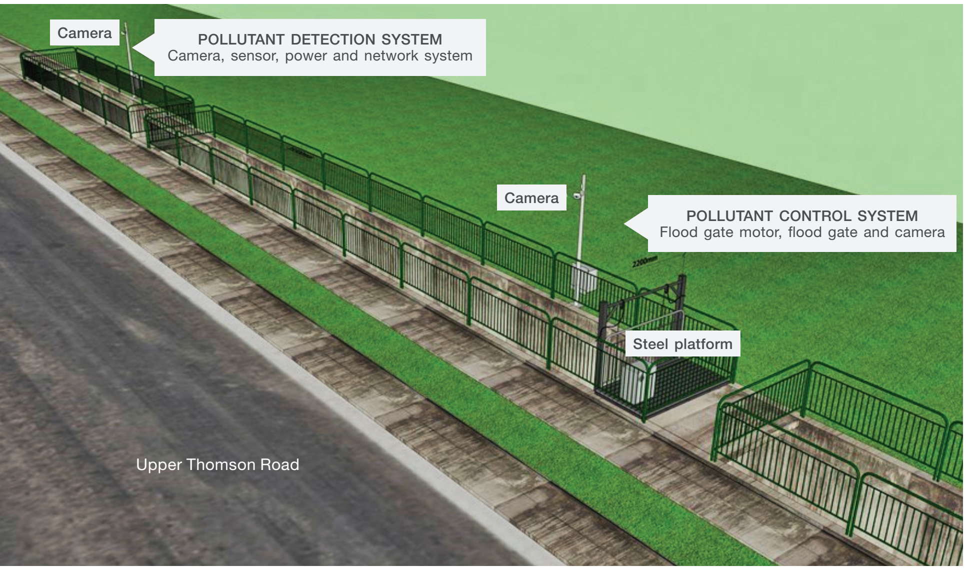

FIG. 1: Perspective view of the pollution detection and containment system

A signature projects under PUB's Active, Beautiful, Clean Waters Programme, Kallang River @ Bishan-Ang Mo Kio Park was transformed from a concrete canal into a naturalised river that is integrated with the adjacent parks to create a recreational space for residents.

In recent years, PUB has encountered cases of polluted discharge (most commonly paint and oil) originating upstream of the river. When the pollutants flow into the river, they create aesthetic problems and unwanted public attention. The removal of these pollutants also poses a challenge.

To mitigate these issues, Oneberry Technologies (Oneberry) and PUB embarked on a testbedding project to deploy a pollution detection and containment system (PDCS). Consisting of water quality sensors, closed-circuit television (CCTVs) and a floodgate, PDCS functions holistically to detect, evaluate and contain polluted discharges before they enter the river (Fig. 1).

The water quality sensors monitor parameters such as dissolved oxygen, electrical conductivity, pH and ammonium/ammonia concentration, while optical turbidity and refined oil sensors detect the presence of volatile organic compounds which are found in polluted discharge. CCTVs were installed to monitor visual changes in water quality and the water level in the drain. When water quality measurements exceed acceptable levels, the floodgate would be lowered to contain the polluted water and prevent it from flowing downstream.

To test the efficacy of the system, a prototype was installed at a subsidiary concrete drain along Upper Thomson Road (Fig. 2). Eight months of monitoring and analysis was first carried out to establish the baseline (set at the 95th percentile) of the various water quality parameters.

The PDCS prototype was officially commissioned and tested in June 2017. It was configured to send real-time alerts, and visual verification was carried out via CCTV footage. When polluted discharge was detected, the floodgate was remotely operated to contain the flow.

From June to November 2017, a total of 262 incidents were recorded. Of these, there were 154 polluted discharge cases, 89 spike alerts and 19 false negative alerts. Spike alerts were incidents where water quality parameters were detected to exceed allowable limits but returned to normal condition within five minutes from the first alert. False negative alerts were incidents when discoloration in the flow was observed via CCTV footage but real-time alerts were not triggered. In the event of polluted discharge, the floodgate was successfully activated to prevent the polluted water from flowing downstream.

“During the test period, we observed that the sensor performance was affected by the accumulation of sediment around the sensors. This was one of the reasons for the spike alerts,” said Brigette Capacia, principal investigator of the project. “To improve the sensor performance, we have since stepped up the frequency of calibration and maintenance.”

Oneberry and PUB are still operating the prototype system to assess its long-term performance.

FIG. 2: The pollution detection and containment system installed at Upper Thomson Road

LIST OF ABBREVIATIONS, ACRONYMS, SYMBOLS & UNITS

Acronyms & abbreviations

ABC Waters	Active, Beautiful, Clean Waters
ACU	Algae control unit
AOB	Ammonia oxidising bacteria
AOP	Advanced oxidation process
BAF	Biologically activated media filtration
BOD	Biochemical oxygen demand
CASP	Conventional activated sludge plant
CBD	Collimated beam device
CCKWW	Choa Chu Kang Waterworks
CCTV	Closed-circuit television
CEC	Contaminants of emerging concern
CFP	Call-for-proposal
CHP	Combined heat and power engine
COD	Chemical oxygen demand
COI	Cytochrome c oxidase subunit I
CRP (Water)	Competitive Research Programme (Water)
DBOO	Design, Build, Own and Operate
DC	Dewatering centrate
DNA	Deoxyribonucleic acid
DTSS	Deep tunnel sewerage system
EBPR	Enhanced biological phosphorus removal
EDI	Electro-deionisation
EDR	Electrodialysis reversal
EISFM	Electrical Impedance Spectroscopy Fouling Monitor
EMA	Energy Market Authority
EPT	Enhanced primary treatment
EWTCOI	Environmental and Water Technology Centre of Innovation
FAMS	Fish activity monitoring system
FISH	Fluorescence in-situ hybridisation
FST	Final settling tank
GAO	Glycogen accumulating organism
GPS	Global positioning satellite
GWRC	Global Water Research Coalition
HAB	Harmful algal bloom
HDB	Housing Development Board
HTS	High-throughput sequencing
IoT	Internet of Things
IWSDF	Industrial Water Solutions Demonstration Fund
KMEDP	Keppel Marina East Desalination Plant
LIDAR	Light Detection and Ranging
MBR	Membrane bioreactor
MF	Microfiltration
NDMA	N-Nitrosodimethylamine
NEA	National Environment Agency
NEWRI	Nanyang Environment & Water Research Institute
NOB	Nitrite oxidising bacteria
NRF	National Research Foundation
NTU	Nanyang Technological University
NUS	National University of Singapore
OBP	Oxidation by-product
PAO	Polyphosphate accumulating organism
PDCS	Pollution detection and containment system
PRO	Pressure retarded osmosis
PST	Primary settlement tank
PUB	PUB, Singapore's National Water Agency
R&D	Research & development
RED	Reverse electrodialysis
RFP	Request-for-proposals
RO	Reverse osmosis
SCADA	Supervisory control and data acquisition
SCELSE	Singapore Centre for Environmental Life Sciences Engineering
SIWW	Singapore International Water Week
SMTC	Singapore Membrane Technology Centre
SRT	Sludge retention time
START	Separation Technologies Applied Research and Translation Centre
SWRO	Seawater reverse osmosis
THP	Thermal hydrolysis process
TSS	Total suspended solids
UASB	Upflow anaerobic sludge blanket
UAV	Unmanned aerial vehicle
UF	Ultrafiltration
ULF	Ultra-low frequency
UNSW	University of New South Wales
UV	Ultraviolet
VFD	Variable frequency drive
VOC	Volatile organic carbon
VSP	Variable Salinity Plant
WHO	World Health Organization
WRN	Water Reclamation Network
WRP	Water Reclamation Plant
WSCC	Water Supply Control Centre
WSN	Water Supply Network
WSP	Water Supply Plant

Symbols & units

G_{DP}	Conductance of the membrane's diffusion polarisation layer
m^3	Cubic metre
m^3/day	Cubic metre per day
ΔP	Differential pressure
Hz	Hertz
kHz	Kilohertz
kWh/m^3	Kilowatt-hour per cubic metre
L	Litre
µg/L	Micrograms per litre
µS/cm	Microsiemens per centimetre
mgd	Million (imperial) gallons per day
ng/L	Nanogram per litre
nm	Nanometre

PUB COLLABORATORS

Universities, research centres & international organisations

Advanced Environmental Biotechnology Centre	Singapore
Advanced Water Management Centre	Australia
Agency for Science, Technology and Research	Singapore
American Water Works Association	USA
Canadian Water Network	Canada
Centre for Advanced Water Technology	Singapore
Centre for Environmental Sensing and Modeling	Singapore
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International Water Association	UK
International Water Resources Association	USA
KAUST Water Desalination and Reuse Center	Saudi Arabia
KWR Watercycle Research Institute	Netherlands
Massachusetts Institute of Technology	USA
Michigan State University	USA
Monash University	Australia
Nanyang Environment and Water Research Institute	Singapore
Nanyang Technological University	Singapore
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New Energy and Industrial Technology Development Organisation	Japan
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Singapore Membrane Technology Centre	Singapore
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Singapore Water Association	Singapore
Singapore-MIT Alliance for Research and Technology	Singapore
Singapore-Peking-Oxford Research Enterprise for Water Eco-Efficiency	Singapore
Stanford University	USA
STOWA Foundation for Applied Water Research	Netherlands
SWELIA Association	France
The Commonwealth Scientific and Industrial Research Organisation	Australia
Toray Singapore Water Research Center	Singapore
Toshiba Aqua Research Centre	Singapore
Trent University	Canada
Tropical Marine Science Institute	Singapore
Tsinghua University	China
UK Water Industry Research	UK
United States Environmental Protection Agency	USA
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Virginia Polytechnic Institute and State University	USA
Water Research Australia	Australia
Water Research Commission	South Africa
Water Research Foundation	USA
Water Services Association of Australia	Australia
World Health Organization	International

Water utilities, agencies & companies

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Affordable Water	New Zealand
Air-Cure (Singapore)	Singapore
Amiad Filtration Systems	Israel
Anaergia	Canada
Aqleo	Singapore
Aquaporin	Denmark
Aromatrix Technologies	Hong Kong
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ASB Biodiesel	Hong Kong
Astronics Technologies	Singapore
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Boerger Pumps Asia	Singapore
Boustead Salcon Water Solutions	Singapore
BrightSource ICS2	Israel
Camp Dresser & Mckee	USA
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Daily Life Renewable Energy	Singapore
Darco Water Technologies	Singapore
Dayen Oil Water Technologies	Singapore
Deltares	Netherlands
DHI Water & Environment	Singapore
Doosan Heavy Industries & Construction	South Korea
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D-RON Singapore	Singapore
Ecosen Solutions	Singapore
Ecospec Global Technology	Singapore
ecoWise Technologists & Engineers	Singapore
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Houstrek Engineering	Singapore
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Huber Technology	Germany
Hydrovision Asia	Singapore
Hyflux	Singapore
Hyosung Corporation	South Korea
IBM	USA
Ikari Services	Singapore
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Justpure	Canada
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Kemira	Finland
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K-One Industries	Singapore
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Liqtech	USA
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Microvi Biotech	USA
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MWH Asia Pacific	Australia
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NGK	Japan
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Oneberry Technologies	Singapore
Optiqua Technologies	Singapore
OptiSense	United Kingdom
Orange County Water District	USA
PA Watertech	Singapore
Pall Corporation	USA
Pôle EAU	France
PulverDryer Technologies	USA
PWN Technologies	Netherlands
Rand Water	South Africa
Rehau Unlimited Polymer Solutions	Germany
Renewed Water Minerals	South Korea
Rigel	Singapore
ROTEC	Israel
RPMTech	South Korea
Saline Water Conversion Corporation	Saudi Arabia
Scinor Water America	USA
Sembcorp Industries	Singapore
Severn Trent Water	United Kingdom
SIF Technologies	Singapore
Sinomem Technology	Singapore
Sound Global	Hong Kong
Star Water Technologies	Singapore
Starfish Enterprises	USA
Strebl Energy	Singapore
SUEZ	France
Sunseap Enterprises	Singapore
SystemNix Asia	Singapore
Tamura Corporation	Japan
Technologiezentraum Wasser (TZW)	Germany
Teijin	Japan
Toray Chemical Korea	South Korea
Toshiba	Japan
Trenchless Technology	Singapore
Tritech Engineering and Testing	Singapore
Trojan Technologies	Canada
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United Water Technologies	Singapore
USP Group	Singapore
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