PUB
SINGAPORE'S
NATIONAL
WATER AGENCY

INNOVATION IN WATER SINGAPORE

JANUARY 2022 | VOLUME 12

CLOSING THE LOOPS

Towards More Sustainable Water

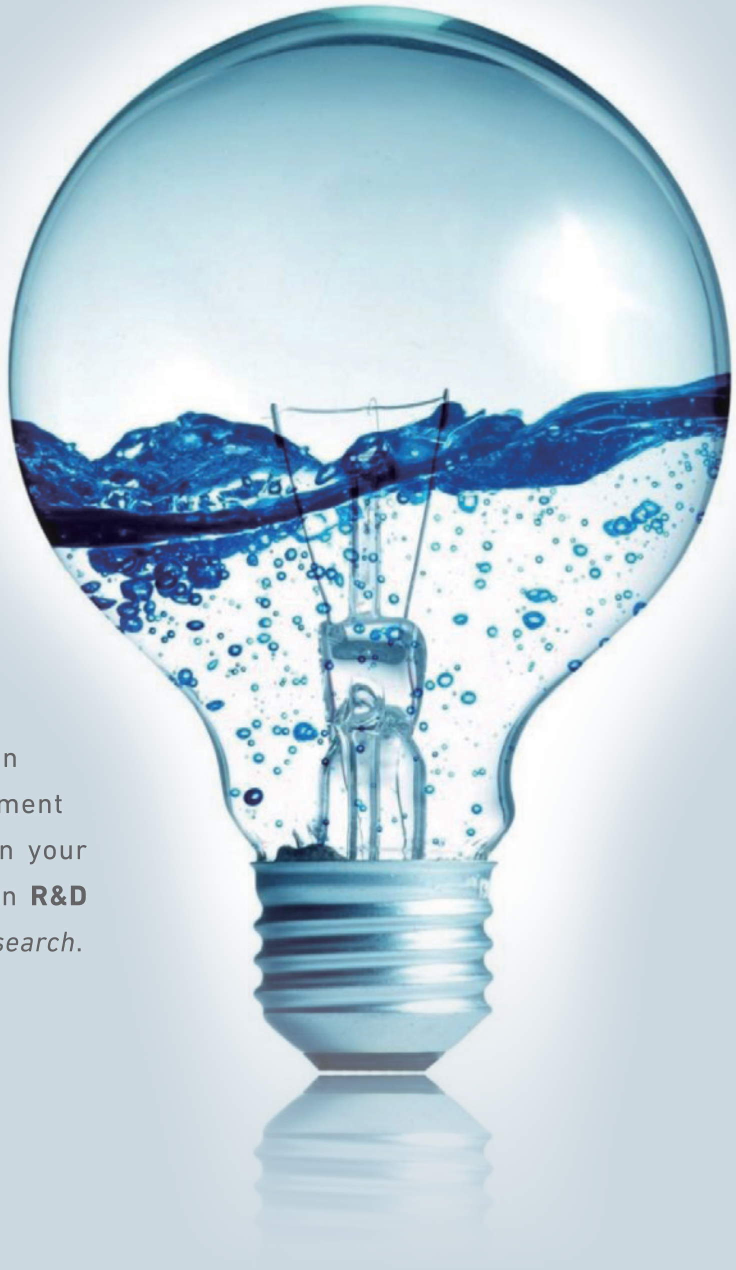
Floating solar farms on Tengeh Reservoir

INNOVATION
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 supply good water, reclaim used water, tame storm water and resist rising seas.

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*.



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PUB Collaborators

Innovation in Water, Singapore

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

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WELCOME MESSAGE

Bernard Koh Eng Wah
Assistant Chief Executive
(Future Systems and Technology),
PUB, Singapore's National Water Agency

Dear readers,

As the 12th edition of "Innovation in Water, Singapore" comes hot off the (virtual) press, the world is now quite a different place since the last edition. The global pandemic has forced us to re-evaluate the resiliency of our water systems. At the same time, effects of climate change that are becoming more pronounced in recent years around the globe have called for actions to be taken to improve our relationship with the environment.

PUB, Singapore's national water agency, is one of the few utilities in the world to manage and close the entire water loop, by including NEWater (recycled used water) and desalinated seawater to its portfolio of water sources to meet the nation's demand. These sources are weather-resilient, but require more energy to treat and produce and therefore increase our carbon footprint.

Besides closing the water loop, we will need to close the carbon and waste loops by being more efficient in how we use resources and reducing the water sector's energy requirements and carbon emissions. In this edition, we share our recent experiences investigating related technologies, including co-digestion of used water sludge and food waste to increase biogas production, anaerobic membrane bioreactor (AnMBR) coupled with anaerobic ammonia oxidation (ANAMMOX) to reduce aeration energy and sludge generation, pressure retarded osmosis to generate energy from seawater and NEWater brine, and data analytics for process optimisation.

Significant advances toward these goals will be realised when the Tuas Nexus facility comes online. The Tuas Nexus is a facility that is designed from the ground up to harness the potential synergies of a water-energy-waste nexus utilising advanced water and waste management technologies. Ground-breaking ideas and research that have been years in the making will finally be actualised in this state-of-the-art facility.

At the same time, we will increase the availability of more carbon friendly energy sources. There are ongoing efforts to harvest renewable solar energy, through the deployment of solar panels within our water infrastructure and reservoirs. In July 2021, we officially opened one of the world's largest inland floating solar farms on Tengeh reservoir, that can produce sufficient clean energy to meet the energy demands of our local waterworks, making Singapore one of the few countries in the world to have a 100 per cent green waterworks system.

Second, we need to find game-changing ways to reduce, reuse and recycle the carbon and waste materials within the ecosystem. We are exploring new methods and technologies to reduce the net energy and carbon emissions of our operations, as well as recovering useful resources from our water and used water treatment processes through innovation.

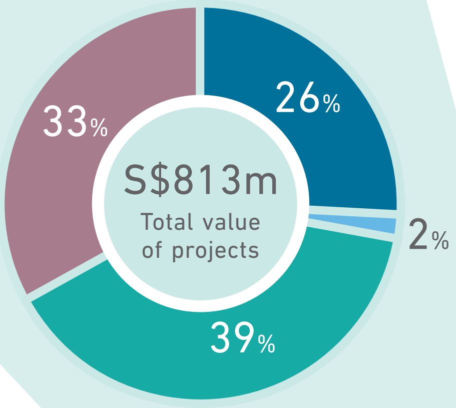
Achieving our sustainability goals depends on an ecosystem of innovative solutions and invaluable collaboration with our network of partners. At PUB, our vision for sustainable water management goes beyond innovation in water. We recognise that the broad impact of climate change accentuates the necessity of energy and waste circularity. Join us, as we work towards closing our waste and carbon loops, while maintaining resilience in our water supply to create a more sustainable future for tomorrow.

Bernard Koh

R&D in Numbers

Since 2002, PUB, together with stakeholders dedicated to solving Singapore's water challenges, have collectively committed more than S$800 million 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, two in every three projects carried out by PUB progresses to implementation or the next development phase.

R&D INVESTMENT (SINCE 2002)



- ● PUB funding
- ● National Research Foundation (NRF) funding
- ● Contribution from Collaborator
- ● Other Government Agencies

ACROSS THE WATER LOOP

25% WATER TREATMENT, DESALINATION & REUSE

23% USED WATER TREATMENT

20% WATER QUALITY & SECURITY

10% NETWORK MANAGEMENT & WATER CONSERVATION

10% WATERSHED MANAGEMENT

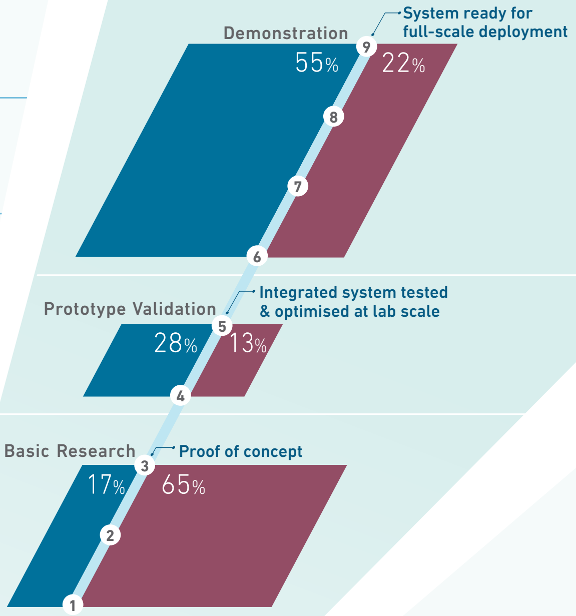
7% SMART TECHNOLOGIES

3% INDUSTRIAL WATER SOLUTIONS

2% OTHERS

ACROSS THE TECHNOLOGY READINESS SPECTRUM

SPECTRUM COMPRISES 9 TECHNOLOGY READINESS LEVELS[a] (TRLs)



- ● PUB-funded projects
- ● NRF-funded projects

710 projects in collaboration with partners from **27 countries**

78% of projects increase in TRL when completed

TWO IN 3 completed projects progresses to implementation or the next development phase

---

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

Statistics valid as at Dec 2020

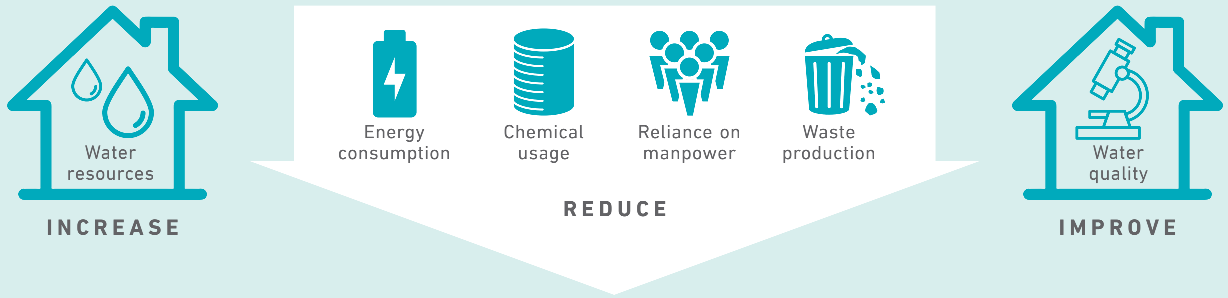
Targets & Focus Areas

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 across 10 technical domains. These include three new domains on Climate Change Mitigation, Climate Resilience and Coastal Protection, and Waste Reduction and Resource Recovery, which have been added as part of PUB's efforts to support Singapore in advancing its national agenda on sustainable development.

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 approach to R&D



Target
Operational or R&D goals

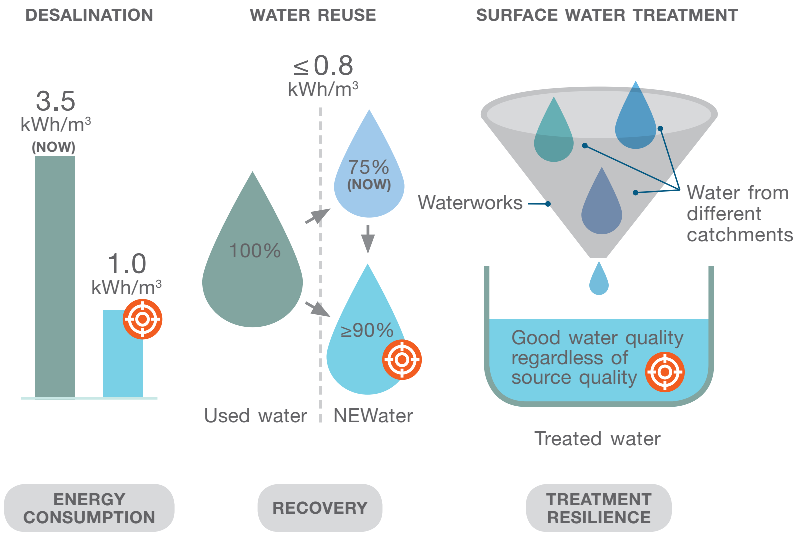
R&D area of interest
Technologies/solutions that can potentially help PUB meet its operational targets in the identified domains

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 reservoir water, the 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

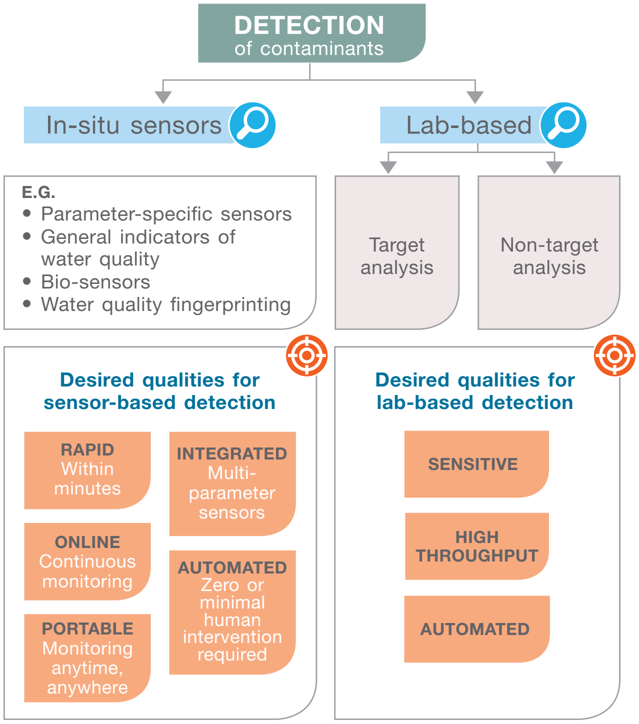
Process improvements
- Electrodialysis reversal-reverse osmosis
- Flow reversal

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

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, especially 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

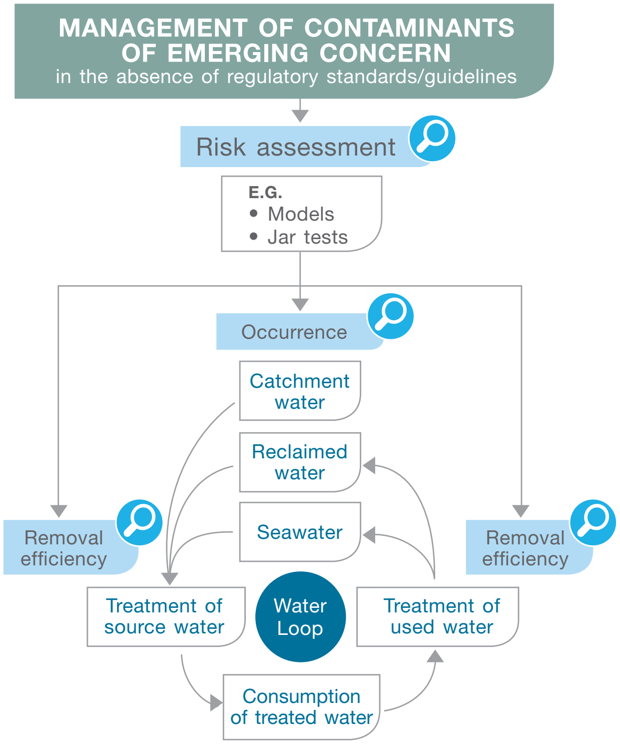
Non-target analysis

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

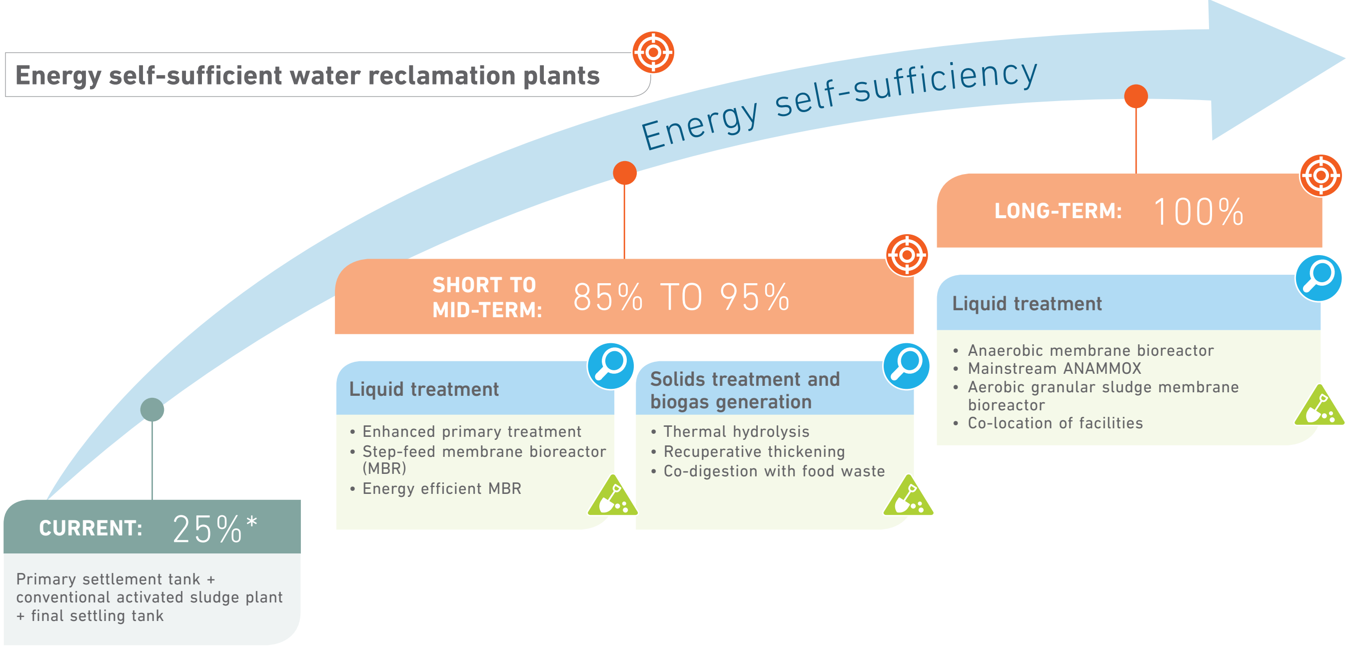
E.G.
- Models
- Jar tests

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. 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: 85% TO 95%

Liquid treatment
- Enhanced primary treatment
- Step-feed membrane bioreactor (MBR)
- Energy efficient MBR

Solids treatment and biogas generation
- Thermal hydrolysis
- Recuperative thickening
- Co-digestion with food waste

LONG-TERM: 100%

Liquid treatment
- Anaerobic membrane bioreactor
- Mainstream ANAMMOX
- Aerobic granular sludge membrane bioreactor
- Co-location of facilities

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

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 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. The first phase of PUB's Smart Water Meter Programme in Singapore will see the installation of some 300,000 smart water meters in new and existing residential, commercial and industrial premises by 2023.

Water Supply Network

DATA-DRIVEN CUSTOMER ENGAGEMENT

- To empower customers to make informed decision about their water usage and receive leak and high usage alerts

INTELLIGENT COMMAND AND CONTROL

- To enhance ground situational awareness for effective resource management and decision making during incident management

SMART WORK PROCESSES

- To increase productivity and reduce manual processes through use of technologies

PROACTIVE ASSET MANAGEMENT

- Proactively survey the health of our assets and develop a maintenance and renewal plan for better leak management

REAL-TIME DIGITAL TWIN

- To monitor network operation and health in real-time (pressure, water quality, flow, service reservoir level and pump operations)
- To enable more accurate network simulations and analyses

Used Water Network

NOWCAST & FORECAST SEWER WATER LEVELS

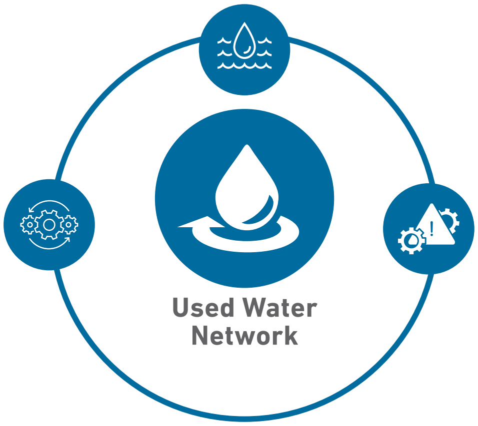
Sewer analytics & modelling system

- 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

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

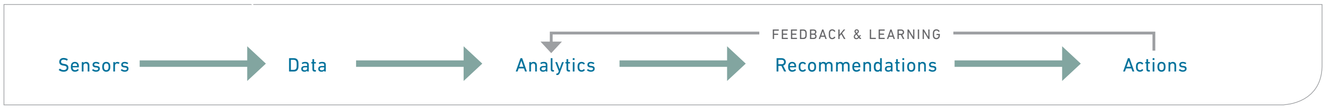


ASCERTAIN RISK & IMPACT OF NEW TRADE PREMISE

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

Workflow envisioned for used water management systems


Sensors → Data → Analytics → Recommendations → Actions

FEEDBACK & LEARNING

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, it is not feasible to build and expand drains to accommodate every extreme rainfall event 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 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 and flood control 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

Climate Change Mitigation

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

To curb rising temperatures, greenhouse gas emissions will need to be curtailed in the decades ahead. Singapore aims to halve its 2030 peak greenhouse gas emissions by 2050, and to achieve net zero as soon as viable in the second half of the century. Although the water sector's emissions are small i.e. less than 1.5% of total emissions in Singapore, PUB is committed to achieve net zero. To achieve this, PUB has put in place a three-pronged strategy to close the carbon loop.

Replace Carbon Emitting Energy Sources

- Floating solar photovoltaics (PVs) on reservoirs and solar PVs on rooftops of PUB installations
- Explore alternative low carbon energy sources

- Floating solar PVs deployment on reservoirs

Reduce Carbon Emissions

- Energy self-sufficiency for used water
- Desalination energy reduction
- Reduce demand in domestic and non-domestic sectors

Refer to on-going R&D efforts under Water Treatment, Desalination & Reuse, Used Water Treatment, Network Management & Water Conservation, Smart PUB and Industrial Water Solutions that can reduce energy consumption or water demand

Remove Carbon through Capture & Utilisation

- Removing CO_2 and other greenhouse gas emissions from used water treatment
- Removal of CO_2 using CCUS technologies that can be integrated with water treatment
- Blue Carbon – Carbon capture by coastal ecosystem

- Capture and utilisation of CO_2 from biogas to produce construction materials
- Capturing CO_2 from seawater through mineralisation

Climate Resilience and Coastal Protection

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

Climate change is expected to raise Singapore's mean daily temperature by up to 5°C by 2100. This is an unprecedented phenomenon, which affects the physical, chemical and biological processes in water and used water systems, as well as the water quality and physical infrastructure, but in hitherto unknown ways. In line with the national goal of building resilience against climate change, PUB seeks to better understand the science in order to guide the formulation of future adaptation strategies. Additionally, as a result of climate change, our sea levels are projected to rise by about 1 meter by 2100. There is hence a need to build new research and operational capabilities in Coastal Protection to enhance Singapore's flood resilience against the combined effects of inland flooding, sea level rise and storm surges.

CLIMATE RESILIENCE

- Understanding climate change science, quantifying the potential impacts, and formulating future adaptation strategies to safeguard water supply

- Impact of climate change on water structural integrity, treatment processes and water quality in the network
- Technologies to strengthen resilience and reduce vulnerability to climate change.

COASTAL PROTECTION

- Laying the foundation for implementing coastal protection works around Singapore's coastline to adapt to sea level rise through
  - development of innovative coastal protection solutions, and
  - studies on Singapore's coastal processes

- Innovative and robust coastal adaptation solutions that incorporate smart systems, multifunctional elements and nature-based solutions; optimise land take and provide flexibility for future incremental build
- Local coastal hydrodynamics and processes to facilitate better design of coastal protection solutions

Waste Reduction & Resource Recovery

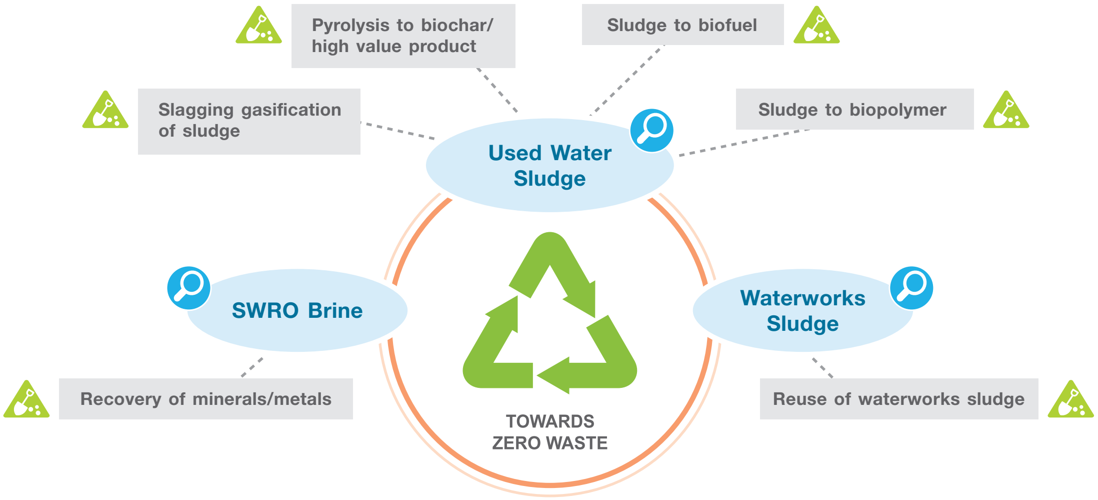
Target | R&D area of interest | Work in progress

In line with Singapore's aspiration to be a Zero Waste Nation, PUB is committed to do our part and close our waste loop. To do this, a two-pronged approach is adopted to not only reduce the amount of waste produced but also find new ways to recover and reuse the waste to useful products. In the spirit of circular economy, a new technology domain is mapped out to guide our effort.

To reduce the amount of dewatered sludge sent to incineration

Short-term Goal (2025)
0.11 kg dry solids/m^3 used water treated
(30% reduction from current level)

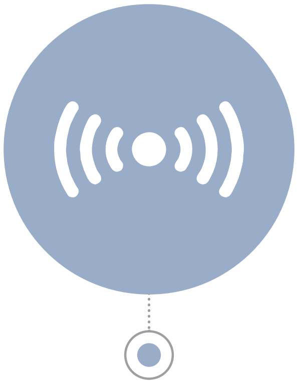
Long-term Goal (2060)
0.08 kg dry solids/m^3 used water treated
(50% reduction from current level)



Smart PUB

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 maximise productivity and enhance operational reliability and security within the water loop.



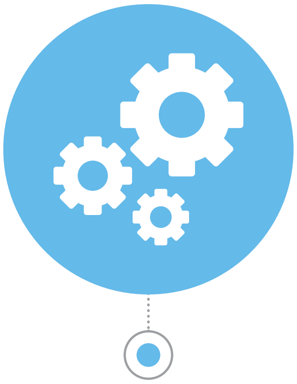
IIoT Sensors for Data Collection

Adequate & Efficient Collection of Data across Water Loop

Real-time monitoring of:

- Rain and weather
- Pressure, acoustic, flow and water quality data for water supply network
- Water quality, flow and level data for sewer network
- Condition monitoring (pumps, drivers, motors)

- X-band radars for rain monitoring
- Event-based acoustic sensors for leak detection
- Biosensors for pollution detection



Automation for Field Operations

Safe, Man-less and Efficient Operations

Automated & autonomous vehicles/platform for:

- Inspection of enclosed pipe of <1m wide and exposed pipeline reserves
- Cleansing and desilting of tanks and pipeline networks
- Minor repair, paintings, etc.
- Operations of valves, hydrant, tidal gates, etc.

- Smart wearables for real-time location monitoring
- Smart goggles: augmented reality for O&M
- Drones for inspection and monitoring

Digital Twin & AI for Insights Analysis

Integrated Digital Twins across Water Loop for Insight and Automation

Provision of insights and recommended actions for:

- Flood and reservoir operations
- Equipment health and predictive maintenance
- Optimisation of water supply and sewer network performance
- Data-driven operations

- Rainfall forecasting
- Process abnormality and water quality prediction
- Equipment fault prediction
- Soft sensors

Industrial Water Solutions

Target

Singapore's industrial water demand will continue to account for majority of our water demand. PUB aims to reduce industrial water demand, by working with large water users, to develop and implement solutions that increase the water efficiencies of industrial processes intrinsically, as well as at the system level. By encouraging the adoption of these solutions, PUB achieves win-win outcomes where industries benefit from recurring savings on their water bills, and PUB is able to ensure a sustainable water supply. Key focus areas include the development of water-*less* processes, increasing the volume of water reclaimed from treated effluent for process reuse, and the use of alternative sources of water (e.g. seawater) for cooling. In addition, synergies can also result from new hybrid processes, such as the recovery of valuable resources from the reuse of industrial wastewater and minimisation of wastewater to be sent for third party disposal.

Target Industries

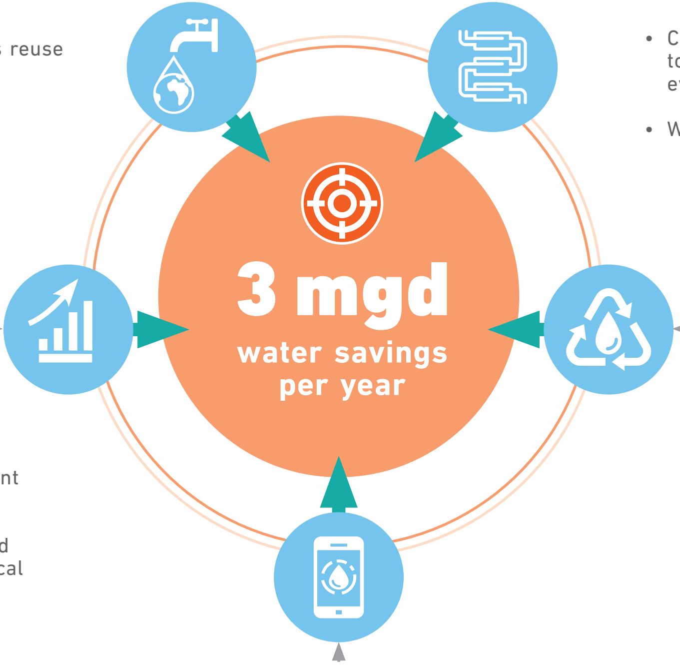
- Power Generation
- Semiconductors
- Petrochemicals
- Pharmaceuticals
- Food and Beverage
- Data Centres

Use of Alternative Sources of Water

- Low temperature distillation
- Variable salinity plant (hybrid rainwater/stormwater blending and treatment with conventional desalination systems and/or electrochemical deionisation)
- Once-through seawater cooling for coastal industries
- Greywater harvesting for process reuse

Water-*less* Processes

- Water-*less* cooling
- Technologies tapping waste heat as energy for cooling processes (Organic Rankine Cycle Engines, etc.)
- Cooling tower augmentation to minimise blowdown and evaporative losses
- Water-*less* clean-in-place systems



3 mgd

water savings per year

Raising the Water Efficiency Indices for Existing Industries

- Design of fit-for-purpose treatment processes
- Provision of technical support and knowledge (e.g. Industrial Technical Guides)

Treat and Reclaim Effluent

- In-situ augmentation of biological process
- Higher freshwater recovery processes (via efficient waste stream management and treatment)
- Modular biological treatment suitable for fluctuating effluent loads
- Implementation of advanced oxidation processes or other methods for destruction of recalcitrant contaminants

Smart Technologies IoT for Enhanced Water Management

- Predictive maintenance/troubleshooting of water management systems to reduce losses and inefficiencies
- Autonomous process optimisation in real-time via machine learning

Collaborate with Us!

PUB welcomes research collaborations that are aligned with the organisation's mission: to supply good water, reclaim used water, tame storm water and resist rising seas. 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 research area(s)**
- 📣 **Opening**
- ✉ **Application platforms**
- 👍 **Featured project**

Research & Development (R&D) Fund

Facilitate 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

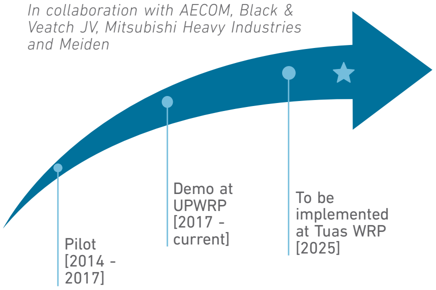
📣 Ongoing application

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

The Integrated Validation Plant for Tuas Nexus and beyond

Process development and validation, smart features and the associated R&D projects with NTU, NUS and Nextan on biosorption, nutrient removal and smart features.

In collaboration with AECOM, Black & Veatch JV, Mitsubishi Heavy Industries and Meiden



Industrial Water Solutions Demonstration Fund (IWSDF)

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

☑

Water consumption should exceed 10,000 m^3/mth	Accomplish 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

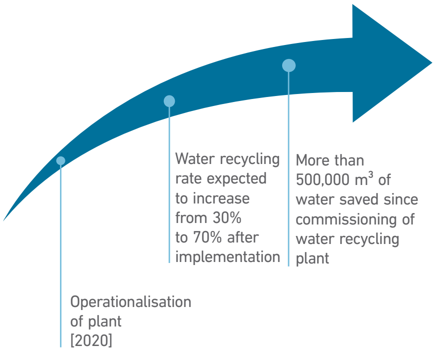
📣 Ongoing application

✉ Download Project Assessment Form from *https://www.pub.gov.sg/research/industrialwatersolutions/funding*

Submit completed form through *PUB_IWSDF@pub.gov.sg*

Wastewater Recycling System

In collaboration with Seagate



Competitive Funding for Water Research

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

- Project to be carried out in Singapore
- Business or organisation is registered in Singapore

Varies across Request-For-Proposals (RFPs); PUB R&D Targets & Focus Areas

TYPES OF RFPs

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

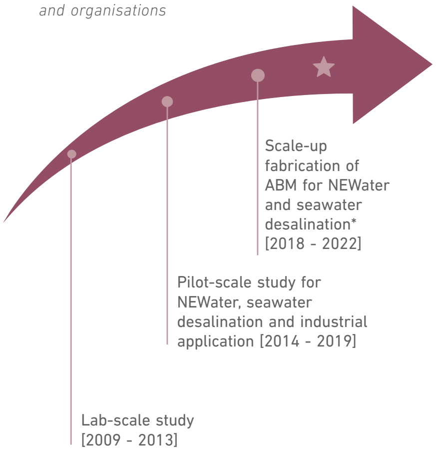
Periodic RFPs, announced through

- 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_crp_water@pub.gov.sg

Aquaporin-based membrane (ABM)

In collaboration with various institutions and organisations



Scale-up fabrication of ABM for NEWater and seawater desalination* [2018 - 2022]

Pilot-scale study for NEWater, seawater desalination and industrial application [2014 - 2019]

Lab-scale study [2009 - 2013]

** Part of the study is funded under Industry Alignment Fund – Prepositioning Funding Initiative*

Living Lab (Water)

Incentivise the adoption of new technologies, facilitating commercialisation

Involve a solution provider and an adopter

Project to be carried out in Singapore

Only Singapore-registered businesses and organisations are eligible

Funding support depends on the types and nature of the organisations

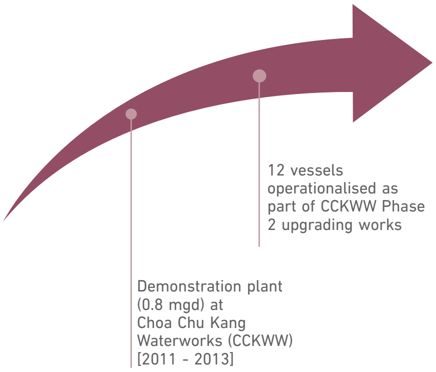
Project shall involve the demonstration of a water technology that is close to operational stage by an adopter

Ongoing application

Joint application* by technology provider and adopter. Indicate interest at
pub_crp_water@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

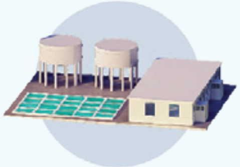
Demonstration plant (0.8 mgd) at Choa Chu Kang Waterworks (CCKWW) [2011 - 2013]

** Either one can apply before a suitable partner is identified and be granted with in-principle approval*

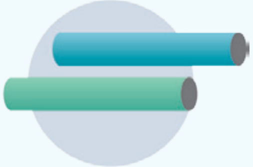
TESTBEDDING OPPORTUNITIES

PUB's operational and R&D-dedicated infrastructure are 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. Facility dedicated to desalination research is also available.

Operational Installations, Sites and R&D-dedicated Facility

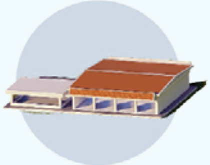

Waterworks


Water Reclamation Plants

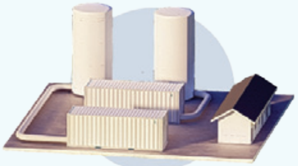

Potable & Used Water Networks


NEWater Factories


Reservoirs


Variable Salinity Plant


Desalination Plant


Tuas R&D Facility
Desalination technologies

✓ Actual operating environments

✓ Technical support from ground staff

TRANSLATION & COMMERCIALISATION

In order to further the development of promising research and capture the value of R&D projects, PUB works with industry partners to support the translation and 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. Some of our translation partners include:

Separation Technologies Applied Research & Translation (START) Centre

The START Centre is set up as a national-level facility to bridge the gap between lab and market, and to provide significant risk mitigation for the commercialisation of separation technologies. START serves as a vital platform for academic and research institutions to transform their innovative technologies into commercial products for key industry players.

Email adil.dhalla@ntu.edu.sg to find out more.

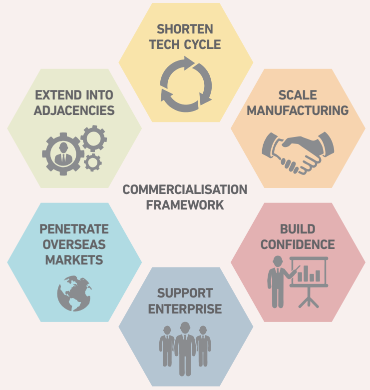
Environmental & Water Technology Centre of Innovation (EWTCOI)

The EWTCOI was set up in October 2006 as a strategic collaboration between Enterprise Singapore and Ngee Ann Polytechnic. Its mission is to partner strategic industry sectors in applied R&D and consultancy projects to translate ideas into practical solutions or innovations for a sustainable environment.

Email ewtcoi@np.edu.sg to find out more.

COMMERCIALISATION

Commercialisation is the process of bringing technologies to the market, realising the value of laboratory research and reaping the economic benefits from R&D investments. It is a multi-stage process that is guided by the Water Technologies Commercialisation Framework and involves different stakeholders such as the Singapore Water Exchange (SgWX) and the Singapore Water Association (SWA):



WATER TECHNOLOGIES COMMERCIALISATION FRAMEWORK

1) Develop technology translation centres (e.g. START and EWTCOI) to bridge the technology translation gap and shorten technology development time.
2) Forge partnerships among players in the water ecosystem to scale up manufacturing.
3) Create a "Living Lab" at PUB's operational installations and R&D facility for technology validation and demonstration.
4) Leverage SgWX ecosystem and support the development of emerging enterprises through incubation/acceleration.
5) Internationalise key technologies/companies through technology promotion at Singapore International Water Week (SIWW) and other initiatives.
6) Expand the uptake of water technologies by adjacent industry sectors through outreach partners like Singapore Membrane Consortium (SG-MEM).

Singapore Water Exchange

The Singapore Water Exchange (SgWX) is a global marketplace for innovative water companies. Established in 2018, it houses a vibrant ecosystem comprising different water industry players that work together to push the frontiers of water innovation. They range from start-ups to MNCs, and cover technology providers, system integrators, accelerators and associations. Currently, SgWX houses close to 30 tenants from 11 countries. Additionally, SgWX hosts a range of activities to accelerate commercialisation and connects companies to business opportunities. These include commercialisation programmes, hackathons, water technology roadshows and market opportunity seminars. We welcome water technology companies to join SgWX and leverage its ecosystem to co-create innovative solutions and discover business opportunities.

Email us at pub_sgwx@pub.gov.sg to find out more.

Singapore Water Association

The Singapore Water Association (SWA) was established in 2004 and is a dynamic collaboration among private sector players intent on bringing a new vibrancy to Singapore's growing water industry. It has close to 300 members and comprises companies and individuals from across the water sector. SWA is an important partner in the technology commercialisation journey. It facilitates strategic partnerships between companies, allows start-ups and SMEs to scale up manufacturing, and provides a springboard for local industry players to internationalise through SWA's overseas networks.

Visit www.swa.org.sg/swat for the SWA eLearning Programme and www.swa.org.sg/swa-digi-expo to explore the world of 24/7 digital water expo.

GENERAL ENQUIRIES ✉

A B *pub_research@pub.gov.sg*

C *pub_sgwx@pub.gov.sg*

Scan for more information

CLOSING IN ON ANSWERS TO SUSTAINABILITY ISSUES

CLOSING THE WATER LOOP:
Tapping on all resources

For Singapore, water security is an existential challenge. As a nation without much natural water resources, Singapore has had to find ways of securing reliable and sustainable sources of water to meet increasing needs. Despite efforts to expand capacity with the addition of Lower Peirce and Upper Seletar Reservoirs to the first reservoir—MacRitchie Reservoir in early 20th century when Singapore was still a British Colony, upon self-rule, the Singapore government recognised that more supply options were necessary. This led to agreements with the Johor State Government for Singapore to import water from Johor and this became one of Singapore's main sources of water at that time.

While the 1962 Water Agreement provides Singapore with imported water until 2061, the extended lead-time for major water supply projects meant that it was necessary to explore complementary solutions to bolster our water supply. These include increasing our catchment areas and building our capacity in rainwater collection. Over a span of more than a century, the number of reservoirs in Singapore has grown to 17 today, with the latest two—Punggol and Serangoon Reservoirs—becoming operational in 2011 (Figure 1). Today, two-thirds of Singapore's land area constitutes catchment areas for rainwater collection, making us one of the few countries in the world to harvest urban stormwater on a large scale.

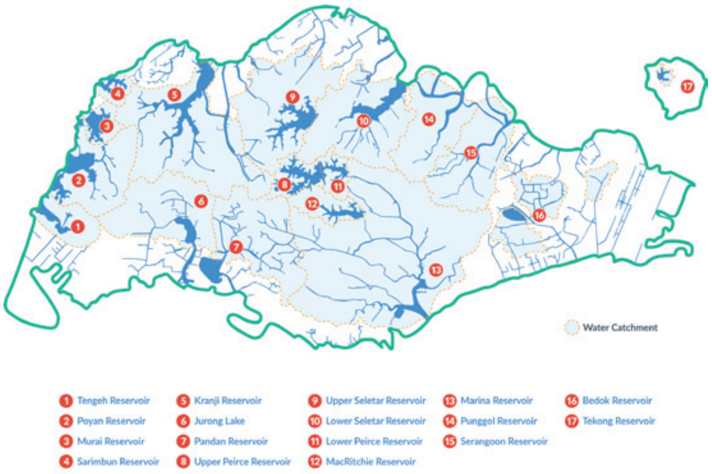


Figure 1. Singapore has 17 reservoirs to store rainwater collected from two-thirds of its land area.

In taking a holistic and integrated approach to water management, Singapore has adopted three key strategies: collect every drop of water, reuse water endlessly and desalinate seawater. The imported water and local catchment water are two of Singapore's Four National Taps. To close the water loop, Singapore developed two other National Taps—NEWater and desalinated water (Figure 2).

As early as in the 1970s, Singapore started exploring the feasibility of recycling used water. However, the membrane technology of the time could not deliver viable solutions. In 1998, PUB set up a team to test the use of the latest proven membrane technology in water reclamation for potable purposes, and by 2000, a full-scale demonstration plant capable of producing 10,000 cubic metres of potable water daily was commissioned. The quality of this reclaimed water, named NEWater, was found to be safe and well within the World Health Organization (WHO) and the United States Environmental Protection Agency's (US EPA) requirements for drinking water.

Three years later, in 2003, Singapore's first two NEWater plants in Bedok and Kranji, launched NEWater to the Singapore public, culminating the journey that began more than 20 years ago. Following this, three other NEWater plants, one at Ulu Pandan Water Reclamation Plant (WRP) and two at Changi WRP, were opened, taking the total number of NEWater plants in Singapore today to five.

Of the Four National Taps, desalinated water has the potential to be a limitless source – as an island surrounded by the sea, desalination is a natural option. Our very first desalination plant, SingSpring Desalination Plant located in Tuas, opened in 2005. We have since added three more desalination plants, with Keppel Marina East Desalination Plant being the latest dual mode plant that can treat both brackish water and seawater (see the next section to find out more). Both NEWater and desalinated water provide Singapore with climate resilient water options and are critical to closing the water loop.

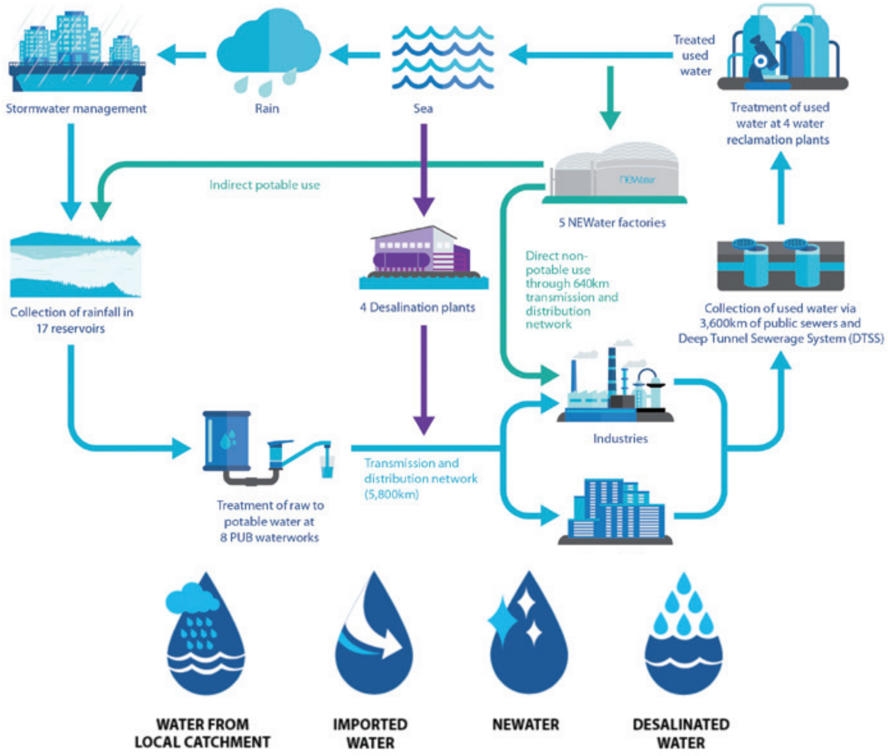


Figure 2. The Four National Taps (shown above) contribute towards closing the water loop in Singapore.

Dual mode facility to boost water resilience

Singapore's current water demand is about 430 million gallons per day (mgd). As we approach 2030 and beyond, we expect the demand for water to continue to rise in tandem with population and economic growth. Ensuring adequacy, resilience and sustainability remains important to Singapore. We are constantly pursuing new approaches to enhance our capability to cater for future water demand and the innovative dual-mode brackish water and seawater desalination strategy is one of them.

Figure 3. The Keppel Marina East Desalination Plant sits underneath a sprawling green park space where panoramic views of the city skyline can be enjoyed. Photo credit: Keppel

The Keppel Marina East Desalination Plant (KMEDP) is unique in its location situated right in a downtown area, saddled by a freshwater reservoir and the sea (Figure 3). Launched in February 2021, this award-winning innovative facility[1] is Singapore's fourth desalination plant—the first-of-its-kind dual-mode desalination plant capable of treating either seawater or freshwater depending on the prevailing weather conditions. During rainy periods when water level in the reservoir is high, the plant treats freshwater drawn from the surrounding Marina Reservoir, while during periods of dry weather, seawater is drawn into the plant for processing. This dual modality allows the plant to operate using less energy when it is not desalinating seawater, thus optimising energy use while maintaining consistent output.

The plant has the capacity to treat up to 30 mgd of potable water. Being the most compact desalination plant in Singapore, the KMEDP occupies an overall land area of only about 2.8 ha, of which 2.4 ha houses its equipment and processes. This desalination plant directly couples both ultrafiltration and reverse osmosis systems, where water from the ultrafiltration process is fed directly to the downstream reverse osmosis process, eliminating the need for intermediate break tanks and pumping stages (Figure 4). The direct coupling of these stages not only saves on the energy costs, it also makes the small footprint of the facility possible.

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[1] KMEDP was named 'Desalination Plant of the Year' at the Global Water Awards 2021

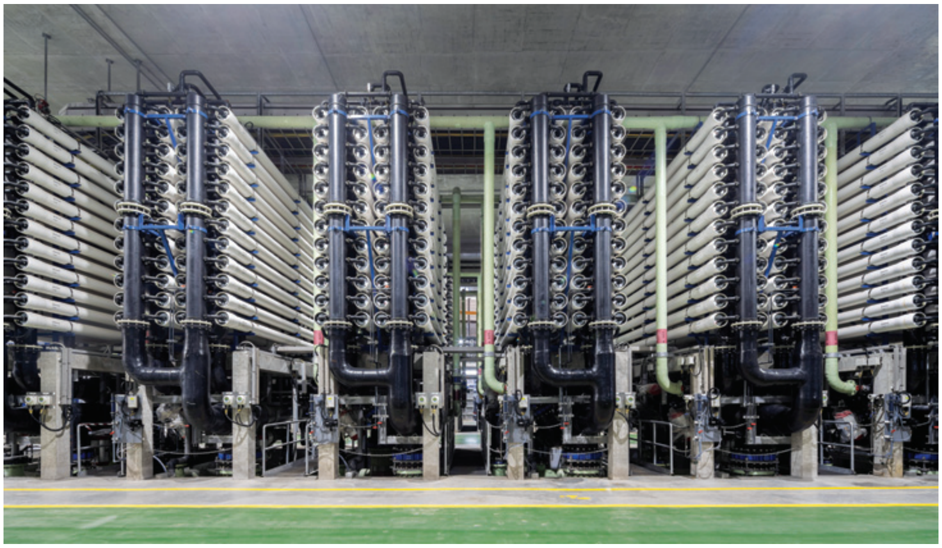

Figure 4. Direct coupling of the ultrafiltration process (on the right) with the downstream reverse osmosis process eliminates the need for intermediate break tanks and pumping, reducing energy and footprint. Photo credit: Keppel

CLOSING THE WASTE LOOP:

Reducing waste and recovering resources

Having closed the water loop, the issue of waste management has also come to the fore. Driven by scarcity, volatile resource prices, and the environmental impact from human activities, Singapore designated 2019 as a Year Towards Zero Waste. It sparked concerted efforts towards implementing new ideas for waste management.

A waste-to-energy (WTE) strategy for the handling of municipal solid waste has been in place in Singapore since 1979, when the first WTE plant at Ulu Pandan was completed with the help of a loan from the World Bank. Since then, four other WTE plants have been built, the last one being Keppel Seghers Tuas WTE Plant in 2009. In the past decades, incineration had been the approach taken to reduce the volume of waste by up to 90% while generating electricity that is sold to the grid.

While this has been effective in limiting the amount of landfill-bound waste in land-scarce Singapore, the amount of waste disposed has nevertheless increased sevenfold over the past 40 years. In 2020, with the Covid-19 pandemic and impact on the economy, about 5.9 million tonnes of waste was generated, down from 7.7 million tonnes of waste in 2019. Even so, this was equivalent to filling more than 11,000 Olympic-size swimming pools. Currently, about 79% of domestic waste generated is incinerated. Together, the four plants incinerate about 7,600 tonnes of waste a day, with the resulting incineration ash and non-incinerable waste being transferred to Semakau Landfill (Figure 5).

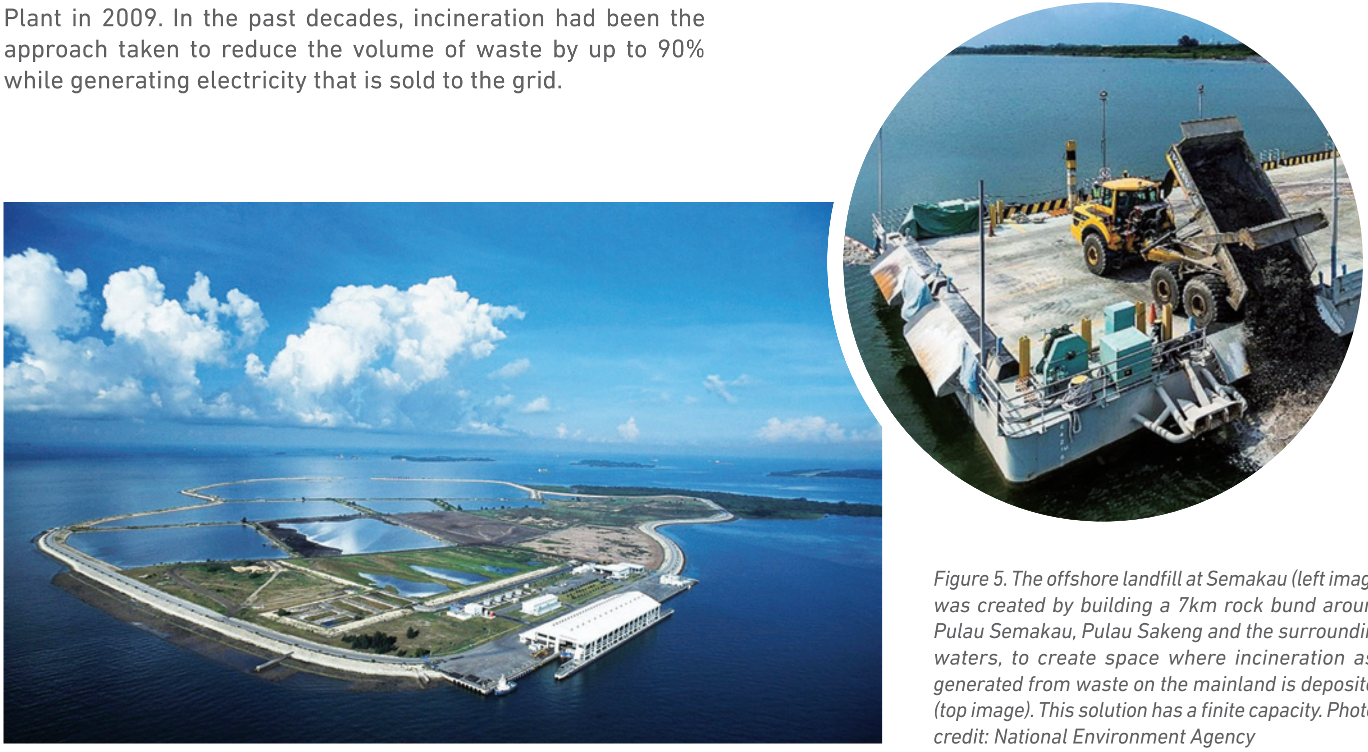

Figure 5. The offshore landfill at Semakau (left image) was created by building a 7km rock bund around Pulau Semakau, Pulau Sakeng and the surrounding waters, to create space where incineration ash generated from waste on the mainland is deposited (top image). This solution has a finite capacity. Photos credit: National Environment Agency

The Semakau Landfill covers an area of 350 ha and is Singapore's only landfill. Accessible via sea, it receives more than 2,000 tonnes of incineration ash from WTE plants and non-incinerable waste daily. As the population grows and development takes place, the amount of waste disposed is expected to increase in tandem. At the current rate of fill, Semakau Landfill will run out of capacity by 2035. In addition, the more waste we incinerate, the higher our carbon footprint and contribution to global warming and climate change. There is an urgent need to reduce what gets sent to landfills from the WTE plants.

Within PUB, two major waste streams of sludge from the waterworks and reclamation plants produce about 6% of Singapore's total landfill waste today. The short-term target is to reduce the amount of sludge sent to incineration by 30% by 2025 and the long-term target is to halve the current amount by 2050. To do this, PUB must not only reduce the amount of sludge produced, but also find new ways to reuse the sludge or ash that is produced. One way is to identify and extract usable resources from waste. Maximising the value of resources by keeping them in use for as long as possible is a key principle of the circular economy—a model that Singapore, and indeed the world needs to embrace to close the waste loop.

To this end, PUB has begun to explore the gasification and pyrolysis of sludge to not only reduce its volume but also to extract usable resources from it. Slag from gasification can be used as construction materials (or NEWSand) for non-structural and structural applications. Biochar from pyrolysis can be used as soil amendment or activated carbon for odour control in our water reclamation plants. Preliminary results from projects with the Nanyang Environment and Water Research Institute (NEWRI) showed that the sludge-derived slag and biochar have low heavy metal leaching rate, making them suitable for the potential applications. The slag also gives sufficient compressive strength when used in construction materials. More details on the projects can be found under the *Research Highlights – Waste Reduction and Resource Recovery* section. Other materials and energy recovery opportunities can also be developed in this area. Going circular will not only reduce waste production, but can result in significant savings on disposal costs and create potential revenue streams from the new products.

CLOSING THE CARBON LOOP:
Carbon Neutrality in Powering the National Taps

As PUB tackles the closing of the water and waste loops head on, our attention is also turned to supporting the Singapore government's target to halve its 2030 peak greenhouse gas emissions by 2050, and aim to achieve net zero as soon as possible in the 2nd half of the century. Meeting the country's energy needs sustainably would be a key challenge in reaching this target. The production of NEWater and desalination are both processes that are energy intensive, and as of now, there are limited options for renewable sources of energy.

Singapore relies heavily on imported natural gas for 95% of our energy needs. With an average wind speed of about 2 m/s, commercial wind turbines are not economically viable; and our relatively narrow tidal range and calm seas limit opportunities for commercial tidal power generation. In addition, heavy port activities restrict the range of ocean energy technologies that can be applied. Without consistently fast-flowing waters, a prerequisite for harnessing hydroelectric power, we are greatly disadvantaged in terms of alternative energy sources.

Being a tropical island that enjoys ample sunshine all year round, solar power is the most likely source of renewable energy. Since 2005, PUB has been actively installing solar photovoltaic (PVs) panels on the rooftops of our facilities to harness solar energy. In 2016, we launched our first floating solar PV testbed, a 1 megawatt-peak (MWp) installation at Tengeh Reservoir, to explore the feasibility of deploying floating solar PV systems on Singapore's reservoirs. Studies conducted showed no observable change in the reservoir's water quality and no significant impact on the surrounding wildlife. This allows our reservoirs to have the dual-purpose of water catchment and storage, as well as clean energy generation.

Through this pioneering R&D effort, PUB is looking to contribute to Singapore's overall sustainability efforts not just in the water domain but in the energy domain as well. As Singapore works towards the national target of quadrupling solar energy deployment to 1.5 gigawatt-peak (GWp) solar capacity by 2025 and 2 GWp solar capacity by 2030, floating PVs are set to make an impact in achieving this target. The testbed at Tengeh Reservoir has revealed that floating PV systems can perform 5-15% better than conventional solar PV rooftop systems due to the cooler reservoir environment, as well as added light reflected off the water's surface. With the positive results, the 60 MWp Sembcorp Tengeh Floating Solar Farm was officially opened in July 2021 (Figure 6). Being one of the world's largest in-land floating solar farm, the amount of energy generated can power about 16,000 four-room Housing Development Board (HDB) flats and reduce carbon emissions by about 32 kilotonnes annually, the same as taking 7,000 cars off the roads. The Tengeh Floating Solar Farm produces enough energy to power all of our local waterworks in Singapore.

PUB will continue to leverage floating solar panels on our reservoirs where possible, balancing against other competing water activities at our reservoirs. Two smaller-scale floating solar farms that are able to generate 1.5 MWp each have also commenced operations at Bedok and Lower Seletar Reservoirs in October 2021. Feasibility studies are planned to be conducted in 2022 for two other large-scale floating solar PV systems at Lower Seletar (100 MWp) and Pandan Reservoirs (44 MWp). PUB will continue to study the environmental impact and feasibility of other reservoirs carefully before exploring their solar deployment potential, and for more energy to be sourced in this manner.

While the creative approaches to solar farming will help overcome some hurdles towards replacing fossil fuels as an energy source, the fact remains that given Singapore's limited land area and competing needs, solar energy will not be enough to close the carbon loop and reach carbon neutrality. Hence improving energy efficiency, managing water demand

Figure 6. An aerial view of the Tengeh Floating Solar Farm which was launched in July 2021. This solar farm has a peak capacity of 60 megawatts, enough to power 16,000 four-room HDB flats for a year. Photo credit: Sembcorp Industries

and reducing the energy requirements of our water treatment processes are key aspects to lowering energy demand while new options of energy supply continue to be explored.

Desalination is the most energy intensive water tap. For every cubic meter of water desalinated, 1.4kg of carbon dioxide is emitted. PUB aims to halve the energy consumption of desalination from the current 3.5 kWh//m^3 over the next few years. Several R&D projects are ongoing in this space, including developing ultra-permeable membranes that could reduce our energy requirements, while achieving the same product water quality. At the same time for used water treatment, we have made significant strides in reducing our energy requirements and increasing the biogas generation from used water sludge. For NEWater production, higher recovery of 90%, up from the current 75%, can be achieved without expanding more energy. Besides technology advances and R&D, public engagements and campaigns continue to be important to drive home the need for water conservation. Coupled with advanced metering infrastructure, which is being rolled out as part of our digitalisation plan, behavioural insights are also being pursued to encourage even greater water conservation. Details on some of the other projects that PUB is exploring to reduce our carbon emissions are available in the *Research Highlights* section both in this magazine and previous editions of Innovation in Water.

Ultimately, we know that even as we reduce our current emissions and replace our carbon emitting fossil fuels with renewable energy sources, we would still be unable to achieve carbon neutrality. To close the carbon loop, we will need a third approach which involves the capture and removal of greenhouse gas. PUB is currently looking at new technologies that can capture and utilise carbon dioxide emitted either directly from our processes or carbon dioxide present in the environment, which can be integrated with PUB's operations. One example is a project that PUB is studying with A*STAR's Institute of Chemical and Engineering Sciences to capture carbon dioxide from biogas for carbonisation into aggregates to produce construction materials. Another project with the University of California, Los Angeles involves the use of the electrolysis technology to react dissolved carbon dioxide with calcium and magnesium in seawater to form solid carbonates, which can be used in construction. The seawater will then be depleted of carbon dioxide and can absorb more of it from the atmosphere. PUB is keen to seek more ideas on the capture, utilisation and storage of carbon that could be techno-economically integrated with PUB's operations for greater synergy. To this end, PUB launched its Carbon Zero Grand Challenge in October 2021, a 45-month programme that seeks to identify, test and scale-up promising technologies for carbon removal with potential for deployment in the next decade. More information on PUB's approach to close the carbon loop and achieve net zero emissions can be found under the *Targets & Focus Areas* section.

WHEN THE LOOPS MEET: A nexus for sustainability

In Singapore, a multi-pronged approach to waste management is coupled with strategies that address our water and energy needs. This strategy is effectively actualised in the design and implementation of Tuas Nexus, a breakthrough facility that will be crucial in taking Singapore to achieve sustainability.

Set to come online in 2025, the Tuas Nexus comprises PUB's Tuas Water Reclamation Plant (TWRP) and NEA's Integrated Waste Management Facility (IWMF). As Singapore's first integrated water and waste treatment facility, Tuas Nexus will be able to maximise energy and resource recovery in ways that previous facilities have not been able to, offering a sustainable solution to help meet Singapore's long-term solid waste management and used water treatment needs. More information on Tuas Nexus and the synergies in co-locating water and waste treatment can be found under the *Facilities* section.

Over the last few decades, PUB has been exploring relentlessly and working innovatively to close the water loop, with great success. Moving forward, PUB is embarking on similar journeys to improve on existing processes and seek new and ground-breaking solutions, to close the carbon and waste loops in Singapore. More research and activities in these areas will enable the circular economy to take root and build up climate, resource and economic resilience to sustain our nation's future.

A SITE FOR SYNERGISTIC SOLUTIONS

A new, multi-use facility, designed to maximise efficiencies and reduce wastage

Tuas Nexus—where novel ideas converge to meet needs

As a small island state with inherent land and resource constraints, the need to ensure sustainability drives many innovations in Singapore. The well-known English proverb, "Necessity is the mother of invention" is especially true here. When a challenge becomes an important need, people are driven to think creatively and collaborate with others to reach a solution.

A prime example of two agencies coming together is the collaboration between PUB and NParks on the ABC Waters project in Bishan-Ang Mo Kio Park to use a limited space optimally. This unique project transformed a large, plain concrete canal and adjacent parkland into a picturesque community park with a natural-looking watercourse running through it. The project met the objectives of both agencies and has become an exemplary case study demonstrating the benefits for synergistic planning and implementation to achieve sustainable results.

PUB is now embarking on another collaboration, this time with NEA, to create the Tuas Nexus (Figure 1). This greenfield project will incorporate PUB's Tuas Water Reclamation Plant (TWRP) and NEA's Integrated Waste Management Facility (IWMF) in a single location. More than just a co-location, this synergistic collaboration with NEA has been designed with resource efficiency and sustainability in mind, to improve energy and resource recovery.

TWRP will receive used water from two separate deep tunnels, constructed under Phase 2 of the Deep Tunnel Sewerage System (DTSS). Used water from the western and southern parts of Singapore will be conveyed through these deep tunnels, entirely by gravity, to TWRP. One of these tunnels—the South Tunnel—will transport mainly domestic used water; while the other tunnel—the Industrial Tunnel—will convey industrial used water.

The plant, equipped with energy-efficient membrane bioreactor systems in both the Domestic Liquids Modules and the Industrial Liquids Modules, will have an initial treatment capacity of 650,000 m^3 of domestic used water (DUW) per day and 150,000 m^3 of industrial used water (IUW) per day respectively. The treated DUW will be used for process needs while some will be further purified to NEWater; and any excess effluent would be discharged to the sea. Meanwhile, the treated IUW will be sent back to industries for reuse, with excess effluent being discharged to the sea.

Designed to be compact in its land footprint, TWRP will have a land-take intensity of 6.15 mgd/ha, making it one of the most compact plants in the world. This is achieved by building upwards; using newer, more efficient technology, and leveraging on the water-energy-waste nexus.

When completed, TWRP will replace the existing WRPs at Ulu Pandan and Jurong. This alone will achieve land savings of up to 85 ha (about the size of 120 football fields) once the existing facilities have been decommissioned. A NEWater factory will also be integrated into TWRP's Domestic Liquids Modules, significantly boosting PUB's current NEWater production capabilities and the robustness of water supply in Singapore without affecting the overall footprint of Tuas Nexus.

In terms of the process, the primary sedimentation tanks—a major component of TWRP—has a footprint that is up to 40% smaller than conventional settling tanks used in older installations. This is achieved with the use of inclined plates to maximise the efficient surface area for solids to settle on within the same tank space. Furthermore, the adoption of Membrane Bioreactor systems at TWRP have allowed used water to be treated to a high quality effluent, using fewer stages and 30% less space compared to conventional treatment process.

Figure 1. An artist's impression of Tuas Nexus.

A greater whole from the sum of connected parts

Used water sludge—the waste by-product of used water treatment—will be co-digested with food waste slurry from the IWMF to produce biogas. Co-digestion will result in a higher biogas yield as compared to digesting used water sludge and food waste separately. The biogas produced will then be conveyed to the IWMF's superheaters to boost its thermal efficiency. The electricity generated will be more than enough to power both TWRP and IWMF, making Tuas Nexus an energy self-sufficient facility that is expected to save more than 200,000 tonnes of carbon dioxide annually, equivalent to taking 42,500 cars off Singapore's roads. Tuas Nexus will be able to produce excess electricity that will be supplied to the national grid.

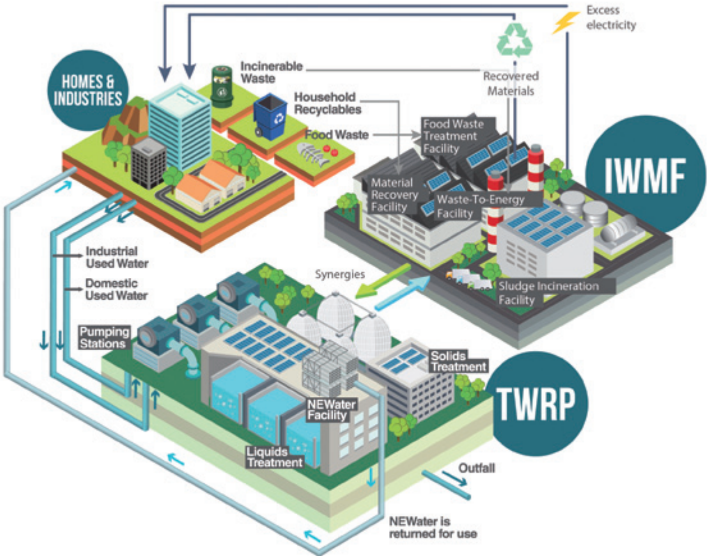

Figure 2. Integration of the WRP and IWMF at Tuas Nexus.

Unlike the current waste-to-energy (WTE) plants which only incinerate municipal solid waste (MSW), the IWMF will process multiple waste streams to improve resource and energy recovery. Apart from MSW, the IWMF will be handling source-segregated food waste and dewatered sludge from TWRP, as well as household recyclables collected under the National Recycling Programme (NRP). This will be the first time that so many different capabilities—used water treatment and reclamation sludge treatment, materials recovery, waste-to-energy incineration—are symbiotically integrated.

New technologies that push the frontiers of efficiency

TWRP will make use of newly developed technologies to achieve productivity gains. Its Domestic Liquids Modules will implement biosorption, or enhanced primary treatment, to increase organics capture for greater biogas production in the digestion process downstream while reducing the energy required in the aeration in the bioreactors (Figure 3). TWRP will also house the world's largest membrane bioreactor with an initial total treatment capacity of 800,000 m^3 per day, equivalent to the volume of water in 320 Olympic-sized swimming pools. The membrane bioreactor will replace separate secondary sedimentation tanks and microfiltration or ultrafiltration membranes, thus saving space while producing a more consistent, higher quality effluent in an energy efficient manner. Read more about the inventor of submerged membrane bioreactor, Professor Kazuo Yamamoto, and his work in the *Interview* section.

Figure 3. Enhanced primary treatment processes with biosorption were trialled on a smaller scale at a demo plant in Ulu Pandan WRP (left), and found to increase energy recovery while reducing downstream treatment energy requirements before being incorporated into the TWRP's design.

Prior to being sent to the digesters, sludge from the membrane bioreactors will undergo thermal hydrolysis. This process, which subjects the sludge to high temperature and pressure followed by a rapid decompression, will enhance the bio-degradability of hard to digest biosolids in the sludge; resulting in higher biogas production. Digesting sludge from TWRP together with food waste from IWMF in anaerobic digestors will result in an almost 40% increase in the biogas production, as compared to digesting them separately.

To further optimise operations, a Supervisory Control and Data Acquisition (SCADA) system from Swedish–Swiss multinational corporation ABB will be deployed to fully automate the treatment process. This system provides visibility of all operations on-site and gives access to process data and alarms, allowing a small operations team to make real-time informed decisions to optimise the facility's performance. The control system will also be integrated with an Advanced Process Control (APC) system using proven mechanistic models and data analytics to analyse trends, identify sub-optimal conditions, and recommend process set points to produce better quality effluent while consuming less energy. In the trials of the APC system at existing plants, 10% energy savings have been observed. Security systems will also be deployed including cyber security solutions that assess threats and test for vulnerabilities to meet Singapore's stringent cyber security requirements.

Leaving no stone unturned

Throughout Tuas Nexus, by-products previously considered as waste will be utilised, wherever possible, to aid the on-site treatment process (such as including food waste in the production of biogas) or reconstituted into a form which can be used in off-site purposes.

As Singapore moves towards more sustainable living, the volume of recyclable waste is set to increase. So apart from food waste and dewatered sludge, Phase 1 of the IWMF will have the capacity to treat 2,900 tonnes of municipal solid waste per day, and have advanced materials recovery capabilities with automated systems for sorting metals, paper, cardboard and plastics.

Non-recyclable waste will be processed using Keppel Segher's proprietary technology, designed specifically to suit the characteristics and requirements of the IWMF. Multiple lanes of waste controlled by an integrated multi-movement system will help to stabilise energy production despite unpredictable input waste quality. The heat recovery boiler is designed with two sections, using both radiation and convectional heat recovery methods to optimise energy recovery efficiency while minimising the corrosive impact of flue gases at higher temperatures. An advanced wet flue gas treatment system will then remove hydrochloric acid and sulfur oxide from the flue gases, while dioxins are captured, removed and completely destroyed in the furnace. This will ensure clean air emissions and potentially meet future tightening of air emission requirement (Figure 4).

Incineration bottom ash (IBA)—a by-product of waste incineration—will be treated to become a material source for civil engineering projects, such as land reclamation, road building and potentially as building construction material. This maximisation of all available resources demonstrates how this facility is moving towards a true circular economy.

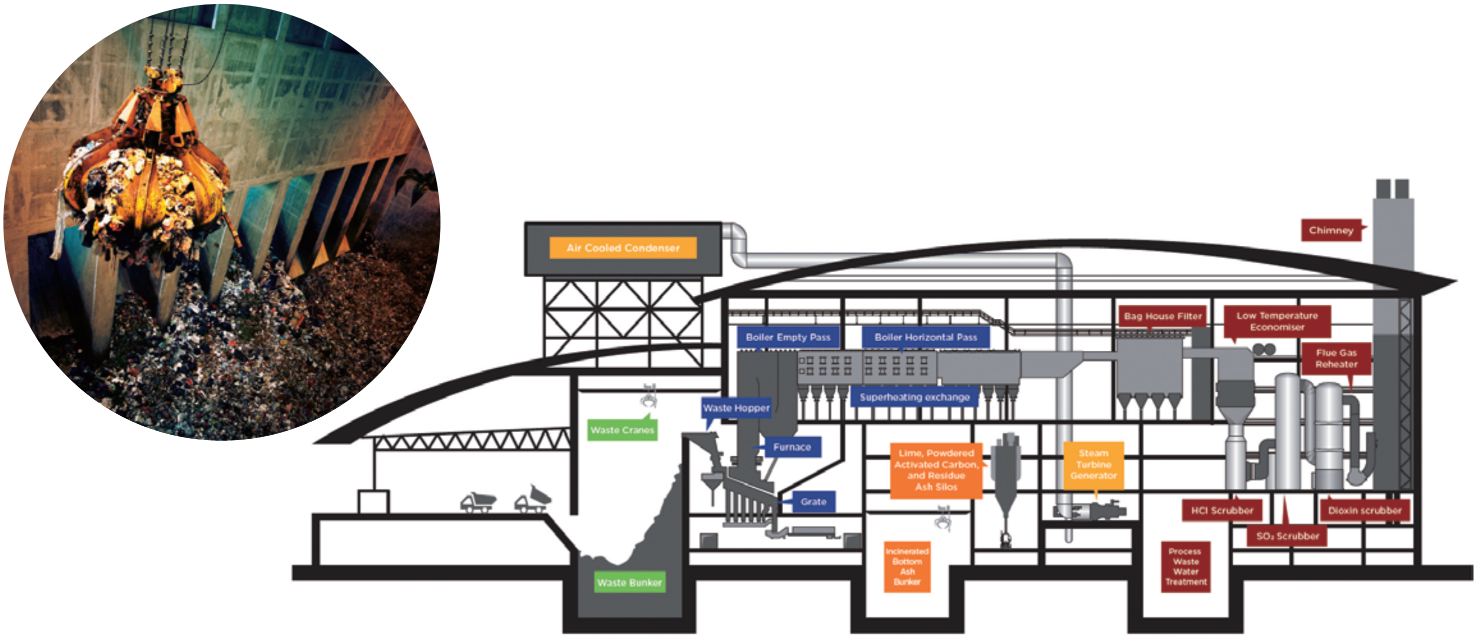

Figure 4. In addition to a Materials Recovery Facility (MRF), the IWMF will also feature a 2,900 tonnes per day Waste-to-Energy (WTE) facility using Keppel Segher's proprietary design which has been tried and tested at the Tuas WTE plant since 2009 (left image). The IWMF will feature air-cooled grates, an advanced combustion system, a segregated boiler system designed to minimise the corrosive impact of flue gases, and a wet flue gas cleaning system to achieve clean air emissions (right image). Photos credit: Keppel (left), National Environment Agency (right)

Harnessing synergies on all fronts

As a whole, Tuas Nexus will allow a number of process synergies to be harnessed from the integration of used water and solid waste treatment:

1. Anaerobic co-digestion of pre-treated food waste from IWMF with used water sludge at TWRP increases biogas generation.

2. The biogas is then combusted in biogas superheaters at the IWMF. This boosts power production capabilities and enhances the plant's overall thermal efficiency.

3. The treatment process of both domestic and industrial used water in TWRP will result in dewatered sludge that is relatively wet, making disposal difficult. To address this, water content of the sludge is reduced in TWRP using dewatering centrifuges. The dewatered sludge is then sent to IWMF via conveyors for incineration and energy recovery. This eliminates the need for transportation out of Tuas Nexus, thereby reducing carbon footprint.

4. Grit and screenings removed from used water at TWRP will be sent to IWMF via trucks for thermal treatment, eliminating the need for these inorganics to be trucked out to another location to be disposed, once again, reducing carbon footprint.

5. Steam from IWMF is sent to TWRP for its thermal hydrolysis process in pre-treatment of sludge, and for hot water generation in greasy waste treatment.

6. Electricity generated by incineration in IWMF will be used to power the operation of Tuas Nexus. Any excess electricity generated will be exported to the national grid.

7. Treated used water from TWRP will be used by the IWMF for various processes, such as for use in wet flue gas treatment system to clean air emissions.

8. Condensate from the sludge-drying process at the IWMF will be channelled to TWRP for treatment.

9. IWMF will supply chilled water to the Tuas Nexus administration building, enabling a more efficient, centralised cooling system.

By designing an intricate network of processes that leverage by-products of other operations, Tuas Nexus is built on the concept of achieving synergy, wherever possible. While these synergies contribute towards closing the water and carbon loops for a more sustainable system, it also allows for the implementation of wider-reaching waste management strategies to then also close the waste loop. Indeed, Tuas Nexus is a clear and compact example of a multi-pronged approach to tackling a series of complex and highly intertwined problems facing the developed world today. It actualises connections on many levels between two agencies to deliver streamlined and beneficial outcomes through the sharing of ideas and resources. Lessons learned through the design, construction and ongoing operations of such a facility will help enhance resource recovery and greenhouse gas reduction initiatives for the future.

INTERVIEW

COMING FULL CIRCLE — A LIFELONG RELATIONSHIP WITH WATER

The Lee Kuan Yew Water Prize is presented at the Singapore International Water Week (SIWW) to recognise the contributions of notable individuals or organisations towards solving the world's water challenges by developing or applying innovative technologies, policies or programmes which benefit humanity. The winner for the Lee Kuan Yew Water Prize 2020, Professor Kazuo Yamamoto, shares his journey and his views on water in a virtual interview from his home in Wakayama, Japan, where he enjoys and appreciates the scenic water views.

What sparked your interest in the area of wastewater treatment and water sustainability?

I was very concerned about the issue of pollution and its impact on the water resources of my country. When I was growing up, water pollution was really serious in Japan. Industrial effluent and municipal wastewater polluted the rivers. As children, we couldn't swim in the river or even play near it. At that time, I felt that we really needed innovation for wastewater treatment in Japan.

When I entered the department of Urban Engineering at The University of Tokyo, it was divided into city planning and sanitary engineering. In Japan, water supply is normally plentiful; the issue is with wastewater. Building wastewater treatment facilities, sewer lines and the like takes a long, long time. There was also a lack of such facilities in the 1970s and 1980s.

The tentative solution for a densely populated area like Tokyo was the Jokaso. [Jokaso is a small-scale onsite treatment plant used traditionally in Japan, in essence a septic tank system]. Using Jokaso for household toilet flushing enabled us to enjoy a pleasant life, but other household used water such as laundry water and water from dish washing were still being discharged into the canals and rivers – what we needed was holistic wastewater management.

What has your research journey been like? What are some of the highlights so far?

My approach to solving the issue of municipal wastewater was biological, rather than physical or chemical. Biofilms and rotating biological contactors (RBC) were being evaluated as replacements for conventional activated sludge technology. Although the potential for biofilms was mainly in smaller plants, they are needed in the rural areas because the construction of sewer pipelines may not be cost effective and takes time. Something like Jokaso, which is an area of interest to me, is ready-made and much quicker to deploy. With de-urbanisation and decreasing population in smaller cities in Japan, Jokaso is now becoming important once again.

Then I started to utilise hollow fibre membrane inside activated sludge aeration tanks, which also gives smaller footprint. I wanted no additional energy requirement with the use of membranes. Of course, this was too idealistic. To eliminate the need for big recirculation pumps, I decided to submerge the membranes. In a laboratory setting, it clogged immediately! But I did not abandon the idea. Eventually, I discovered intermittent filtration. By controlling the input amount and introducing rest time, the filtration process could be sustained. To scale up, we could increase the membrane surface area. It was a matter of finding a balance.

Although the cost of the membranes was very high in the beginning, membranes are easy to produce and I was convinced that the cost would be reduced once the market grew.

When I was around 32 years old, I was seconded to the Asian Institute of Technology (AIT). The AIT is an international university with students from more than fifty countries, including Africa, Southeast Asia, and I taught in English. It was a very good experience for me.

Apart from teaching at the graduate school, I introduced membrane bioreactors (MBR) to the AIT campus and worked on treating campus wastewater at a pilot scale. Some colleagues and I started a membrane group and I did my most advanced research at AIT.

This research was also an opportunity for capability development. I met one of my advisees in Myanmar recently and he shared that he had created a company for wastewater treatment and developed MBR for industrial use. Among my students, one is now a professor in a Chulalongkorn University, and another is an associate professor at Kasetsart University. They continue to conduct MBR research that will help us in the future.

PUB is focused on closing the energy and waste loops, having closed the water loop. What advice or insights would you like to share with PUB in addressing these challenges?

Singapore is a very advanced and compact city-state and is building long-term capabilities to become a Smart Nation. Membrane technology, not only MBR or submerged MBR, is very suitable for water management. A professor from Yamaguchi University has already succeeded in producing hydrogen from reverse electro-dialysis and I think it is promising as a carbon-free hydrogen source. You can also utilise brine produced from the desalination process as an energy source. If we can use natural energy together with other energy sources, we can solve the energy issue.

With Singapore's transformation into a Smart Nation, there are opportunities. Sensors can be everywhere. Membrane technology is very suitable for remote sensing, remote and on-demand management, and maintenance. You can easily monitor the effluent because there are no suspended solids, which means no disturbances for the sensor. This is a cost-effective solution for the management of wastewater quality and is one area I hope to see more development in.

We also need big data everywhere. I am not just talking about treatment plants but also in the environment—the rivers, canals and more. I recommend utilising this sensing system in the natural environment to acquire big data for policy planning. We need a combination of local sensors, satellite sensing, and drone sensing. Wide area sensing is important for blue carbon management because carbon fixation is a hot issue. Singapore is surrounded by sea, so big data on algae growth and seaweed utilisation can help with blue carbon management policies.

What are your other areas of passion? What do you think will help to galvanise the next generation of engineers looking to enter the field?

I recently came across a paper on digital transformation (DX) which mentioned an aesthetic purpose for its use. I was surprised that a DX paper would mention this, but I very much agree. DX and membrane technology should be used to bring out the "aesthetic" aspects of water—healthy water, tasty water, scenic water—to help people appreciate water. DX can be used for entertainment, to shape perception by combining modelling, sensing with gamification. Use it for teaching—especially the young people—and use the data collected to engage people.

PUB can also apply this in its capability development and training. With the current COVID-19 pandemic, movement of people is restricted and a new approach to training should be considered. Virtual reality or mixed reality is a good tool for training. I believe that PUB is capable of developing such programmes for capability development.

Oftentimes, water-related issues are not about technology but rather with water management. When I lived in Thailand in the late 90s, the purification plants had advanced technology, but some of the pipelines were old and operated at low pressure that resulted in unreliable water supply at risk of contamination. With better planning and management of their water supply, their tap water is now potable and safe for drinking.

Do you have any last parting words for our readers?

In my opinion, we need to invest in environment, social and governance (ESG) issues. These are key for future investments. We should consider how to get money (private investments) to help the systems around the world. We need the private sector to be more active in wastewater management. In this sense, we need to consider ESG issues together with public-private partnerships.

WATERSHED MANAGEMENT

As a tropical country with two-thirds of its land area water catchment, Singapore receives abundant rainfall that is collected through a comprehensive drainage network and channelled to reservoirs. Effective storm water 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 storm water 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.

Floating platform at Bedok Reservoir

Measuring rainfall with CCTVs

Using CCTVs with machine learning and deep learning to estimate rainfall

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Rainfall is a complex phenomenon to measure and forecast. Accurate rainfall readings can help to improve rainfall prediction and optimise deployment of flood management resources. However, collecting accurate rainfall readings in all parts of Singapore is particularly challenging due to the spatial and temporal variability of rainfall events in tropical climates.

In addition, traditional monitoring methods such as placing rain gauges in the field require careful installation of the instrument in locations without obstacles and free of rain splash to properly measure precipitation. Rain gauges collect data at the point or location where they are installed and are therefore also unable to yield high-resolution data for rainfall over a large area. This presents an area of opportunity for other rainfall measurement devices that can complement the existing rain gauges and increase the density of the rain monitoring network.

Figure 1. CCTVs are designed to record and monitor scenes. However, by harnessing advanced technologies, they can be also be used as a rain gauge.

PUB collaborated with the Hydroinformatics Institute (H2i) on a 1.5-year project to investigate the potential of real-time rainfall monitoring through street-level CCTV footage. Specifically, this project studied the possibility of adapting six existing CCTVs (see Figure 1) and Internet-of-Things (IoT) enabled cameras as rainfall measurement sensors.

By combining H2i's expertise in machine learning and creating a deep learning model based on VGG19—a convolutional neural network designed for image processing—the CCTVs were able to detect rainfall intensity that was not captured by a nearby rain gauge due to the slight difference in location as illustrated in Figure 2. By combining machine learning and deep learning to analyse the CCTV footage, it was noted that highly accurate spatial and temporal rainfall data could be extracted from the various CCTVs.

Despite the low resolution of the CCTV images (480x320 pixels), the processed data provided distinct categories of rainfall—no rain, light rain, medium rain, heavy rain and extreme rain. As such, the research team was able to conclude that these optical sensors were effective in gauging the intensity of rainfall in real time. Following the promising results from this trial, a scale-up R&D demonstration project to expand the technology to include more of PUB's existing CCTVs across Singapore has commenced.

From April 2021 to October 2022, a total of 150 CCTVs across the island—about half of PUB's surface CCTVs—will be used to develop a system for estimating and showing the rainfall estimates from the CCTV footage in real-time. As part of the project, an optimal cloud computation and cloud storage infrastructure will be configured. In addition, a machine learning framework to enable continuous and semi-automated improvement of the system's performance over time will also be implemented, enabling the system to provide more accurate and robust rainfall estimates from the CCTVs. These efforts could lead to an improved density of the rainfall monitoring network to better support the deployment of PUB's flood management resources during heavy rainfall events in real time.

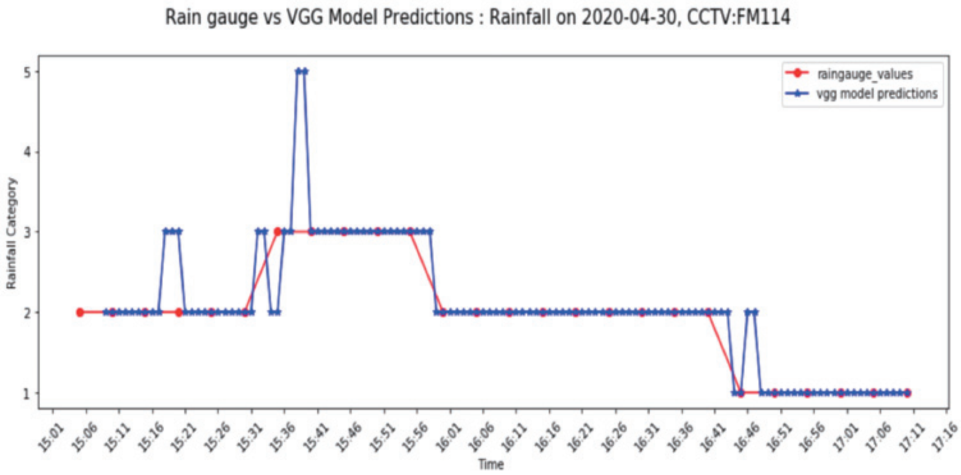

Figure 2. This chart compares the CCTV's rainfall readings (VGG model) with that of a nearby rain gauge. Note that rainfall category 1 refers to no rain and the CCTV and rain gauge are within 123m of each other.

Quantifying the true power of solar energy

The "TruePower Alliance^{TM}" collects real-world data from various photovoltaic systems installed in different climate conditions in order to drive improved performance of solar energy

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Being in the tropical sun belt, Singapore enjoys an average annual solar irradiance of ~1,650 kWh/m^2/year. In 2019, PUB commissioned an upgrade of the photovoltaic (PV) system located on the Sustainable Singapore Gallery roof of Marina Barrage with a nameplate capacity of 84 kWp. It is capable of generating sufficient energy to power approximately 25 four-room Housing & Development Board (HDB) flats per year.

Currently the solar energy supply merges with the existing electrical supply provided by the electrical retailer and is used to power up the loads at Marina Barrage. This PV system is part of PUB's greater efforts to increase PV deployment across their installations, in order to generate green energy to power water treatment processes and reduce carbon footprint.

This PV system is also part of the "TruePower^{TM}" Alliance programme funded by the Singapore Economic Development Board (EDB) and National Research Foundation (NRF). The TruePower Alliance is a partnership between industry collaborators and the Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore (NUS). This alliance was formed to study the "true" output of PV modules and systems under different environmental conditions. Collecting actual data on energy generated by PV systems installed in different climates will help to provide more accurate yield information, rather than relying on rated peak power measured under laboratory conditions.

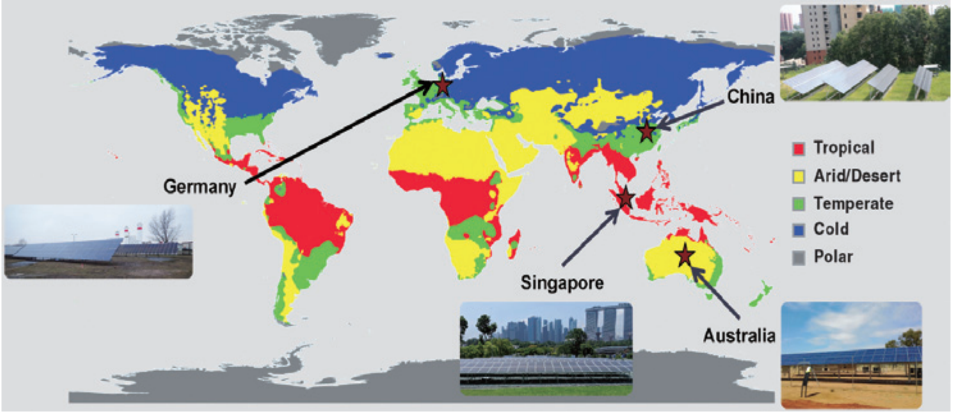

Figure 1. Location of the "TruePower^{TM}" Alliance sites, spread across different climates.

In order to cover the most relevant conditions for PV systems globally, different climatic zones were selected as sites for the test installations, which are operated by SERIS. They include:

- Tropics: Marina Barrage, Singapore;
- Desert: Alice Springs, Australia;
- Temperate I: Friedenshall, Germany; and
- Temperate II: Xinyang, China.

Figure 2. While skyscrapers can be seen in the background, the Marina Barrage PV modules enjoy unblocked access to sunlight due to their unique location at the mouth of the Marina Bay.

The facility at Marina Barrage includes rows of PV modules using different types of solar cell technologies, alongside meteorological sensors and data monitoring capabilities. The influences of the varying weather conditions such as temperature, humidity, irradiance, spectrum, and direct-diffuse ratio, on the performance of the PV technologies are being studied. In addition to the weather parameters, the range of sensors also measure in detail the electrical properties of the deployed solar PV technologies at both module and system levels.

This programme allows SERIS to quantify the performance differences of various PV technologies deployed in the various climate zones. The increased accuracy and granularity garnered from real-world, outdoor performance testing of PV modules helps solar module manufacturers to better understand the long-term energy yield, and durability of their technologies and helps adopters of PV to make informed decisions about the most suitable solar technology for each location. These findings will drive better investment decisions to improve the yield and economic viability of installations as we scale up our solar deployments to reduce carbon emissions.

WATER TREATMENT, DESALINATION & REUSE

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.

Ceramic membrane system at Choa Chu Kang Waterworks

Molecular Design of Reverse Osmosis Membranes for Enhanced Performance

To assess if various modifications of thin-film composite membranes will demonstrate enhanced performance in seawater and brackish water desalination

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Desalinated water is one of Singapore's Four National Taps. As the demand for water continues to increase in tandem with population and economic growth, the role of desalination in providing a sustainable and weather resilient source of water supply for the nation is set to increase.

Reverse osmosis (RO) is the most widely used technology for desalination globally and there is keen interest to make it more efficient so as to reduce the energy requirements. One approach to enhancing the permeability of thin-film composite (TFC) membranes, typically used in water desalination systems, is through the incorporation of nanoparticles. In this R&D project between NUS and PUB, different kinds of nanomaterials were used to modify TFC membranes, in a bid to improve their separation performance.

In the first study, UiO-66-NH2 nanoparticles were incorporated into TFC membranes to produce thin-film nanocomposite (TFN) membranes. The UiO-66-NH2 nanoparticles have an average size of ~100 nm and are a type of metal-organic frameworks (MOFs). The resulting TFN membranes were shown to have greater surface hydrophilicity, a lower degree of cross-linking and provide additional pathways for water molecules across the selective layers.

In brackish water desalination tests, UiO-66-NH2 TFN membranes demonstrated an approximately 50% increase in pure water permeance while maintaining a similar rejection rate compared with the benchmark TFC membranes. In seawater desalination tests, the TFN membranes also demonstrated a higher water flux and salt rejection level compared to the benchmark membranes.

In the second study, the membranes were modified using carbon quantum dots (CQD) and post-treated with hypochlorite. By incorporating Na^+–functionalised CQDs into TFC membranes and applying high-pressure stabilisation, the pure water permeability (PWP) of the membranes improved by about 145% without compromising salt rejection. The combination of amino-functionalised CQDs and post-treatment with hypochlorite enhanced the performance of the membrane, increasing its PWP from 5.5 LMH/bar for membranes modified with amino-functionalised CQDs, to 10.13 LMH/bar for modified membranes with hypochlorite post-treatment. The rejection rate for brackish water also improved for modified membranes that were post-treated with hypochlorite, achieving 98.9% NaCl rejection for 2,000 ppm NaCl solution.

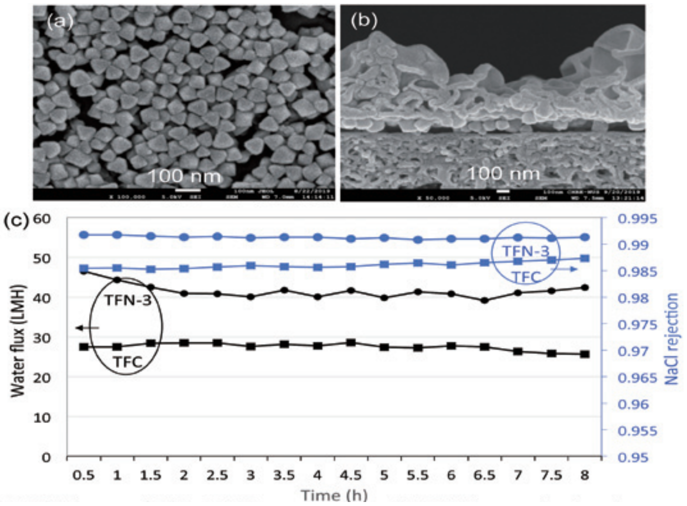

Figure 1. (a) Scanning electron microscope (SEM) image of UiO-66-NH2 nanoparticles, (b) SEM image showing the cross section of UiO-66-NH2 incorporated TFN membranes and (c) performance of TFC and TFN membranes in seawater reverse osmosis processes (Feed: 32,000 ppm NaCl; flow rate: 2 L/min; operation pressure: 50 bar).

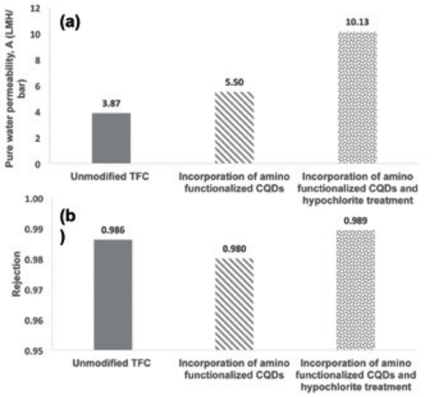

Figure 2. (a) Pure water permeability (Feed: DI water) and (b) salt rejection (Feed: 2000 ppm NaCl aqueous solution) of the unmodified TFC membrane, TFC membranes incorporated with amino functionalised CQDs and TFC membranes incorporated with amino functionalised CQDs after hypochlorite treatment. (Measured at 15 bar after the membranes had been stabilised at 20 bar for 1h.)

The third nanomaterial used to modify TFC membranes was zeolitic-imidazole framework-8 (ZIF-8), a model type of metal-organic frameworks (MOFs). Manipulation of the inner defects within the ZIF-8 nanocrystals (dZIF-8) when incorporated into TFN membranes has been found to reduce transport resistance of water molecules. The optimal TFN membranes consisting of dZIF-8 have a higher water permeance (2.61 LMH/bar) compared with control TFC membranes (1.72 LMH/bar) when tested at 20 bar and room temperature. Meanwhile, it retains a comparable salt rejection of 98.6%. When these TFN membranes are tested under Seawater Reverse Osmosis (SWRO), a higher water flux is obtained compared with levels achieved using TFC membranes. When used as a nanofiller in TFN membranes, the dZIF-8 is easy to prepare and shows excellent water stability.

Making pressure retarded osmosis worth its salt

To leverage on the salinity gradient between seawater brine and brackish water brine to generate energy offset through pressure retarded osmosis (PRO)

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Freshwater—a source of sustenance—is becoming scarce due to rapid global urbanisation. Meanwhile, climate change has altered rainfall patterns and led to extreme weather events in many regions worldwide. Against this backdrop, seawater desalination is gaining more attention as a climate-independent, sustainable source of water.

Among the known desalination techniques, seawater reverse osmosis (SWRO) stands out against conventional distilling techniques. However, there are two challenges presented by SWRO—its high energy requirement and the disposal of its by-product, brine.

While recent development and improvement of membranes and energy-recovery technologies have led to significant cost reductions, energy costs still account for about 50% of the operating cost of a seawater desalination plant. The energy consumed by SWRO process in large-scale desalination plants ranges from 2.0 - 3.5 kWh/m^3, making it the most energy-intensive method for the production of fresh drinking water.

The other issue is the handling of SWRO brine that results from the seawater desalination process. At 40% recovery rate, the amount of SWRO brine is 1.5 times more than desalinated water, with a salt concentration approximately 1.66 times higher than that of the seawater. Discharging brine into the sea without proper control and mixing would adversely impact the marine ecosystem. PUB has a comprehensive brine management and monitoring system to ensure that desalination brine is treated properly and complies with environmental regulations when discharged into the sea.

PRO is being researched as a way to solve these two problems simultaneously. PRO can produce energy from the salinity gradient resulting from the difference in salt concentrations between two solutions. In Singapore, brine from the seawater desalination plant and brine from the NEWater factory provide solutions with different salt concentrations for use in energy production to offset energy costs at desalination plants. Previously viewed solely as a problem, effluent is now a resource for energy production. Commercialising this technology can reduce the energy cost of seawater desalination by more than 10%. Unlike solar energy—another renewable source being tapped for plant operations—this source is not weather-dependent and provides a predictable amount of energy all year round.

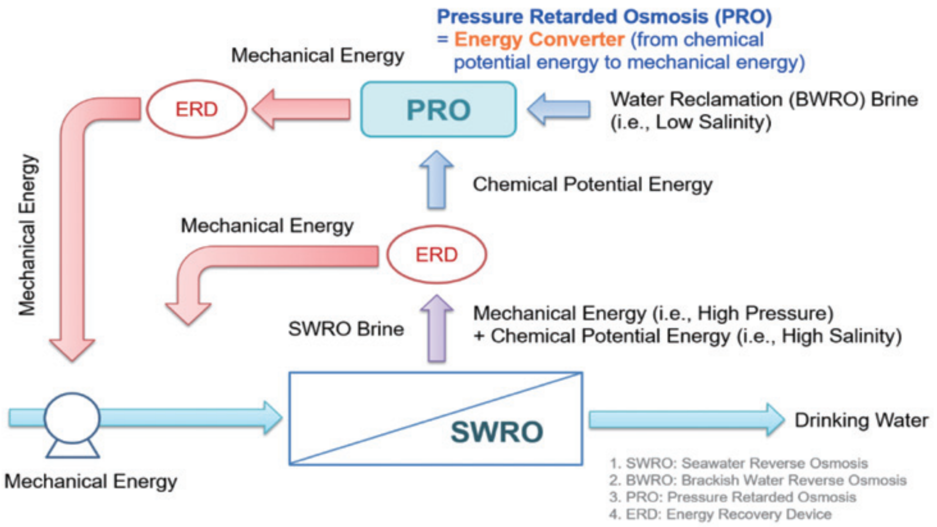

Figure 1. Energy recovery based on high salinity PRO in an SWRO desalination process.

After passing through an energy recovery device (ERD), the seawater desalination brine is mixed with NEWater brine and its salinity is lowered by about 70%—a level where it can now be discharged to sea. The effluent treatment process produces energy instead of incurring cost, contributing to overall cost reductions.

Research is currently underway to optimise the design and operational parameters of the SWRO-PRO-BWRO desalination process for use in large-scale plants. In particular, in-depth study into novel technologies for pre-treatment and PRO membrane fouling control is a focus area in this project as fouling is a critical problem restricting the performance of PRO systems. An energy management system will also be developed as part of the project for real-time analysis of the energy flows to maximise energy efficiency. Findings from these studies will be used in a techno-economic assessment to determine the economic feasibility of the system and enable SWRO-PRO-BWRO hybrid desalination processes to scale up economically.

USED WATER TREATMENT

Besides discharging treated used water into the sea and relying on the natural hydrologic cycle to recycle the water, PUB also shortens the natural water 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. PUB is also looking into digital technologies to help improve the performance of the treatment process and to enhance workplace processes.

Kranji Water Reclamation Plant

Combining waste products for improved biogas production

Combining used water sludge and food waste for more efficient biogas production—Ulu Pandan Co-digestion demonstration plant

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Currently, food waste accounts for about 11% of the total waste generated in Singapore. Notably, only around 19% of the food waste is recycled, with the remainder being incinerated at waste-to-energy plants to generate power. The resultant ash is subsequently disposed in landfill. By using food waste in the production of biogas together with used water sludge generated from municipal water reclamation plant, more energy can be recovered, resulting in higher energy yields and a reduction in waste by-products.

Supported under the TechPioneer Scheme through National Research Foundation (NRF), Singapore's first full-scale demonstration project for co-digestion of used water sludge and food waste was established at PUB's Ulu Pandan Water Reclamation Plant. The two primary goals of the project were to:

1. compare the output of biogas from co-digestion with that of sludge and food waste separately; and
2. establish the best ratios of food waste to sludge for optimum results in co-digestion.

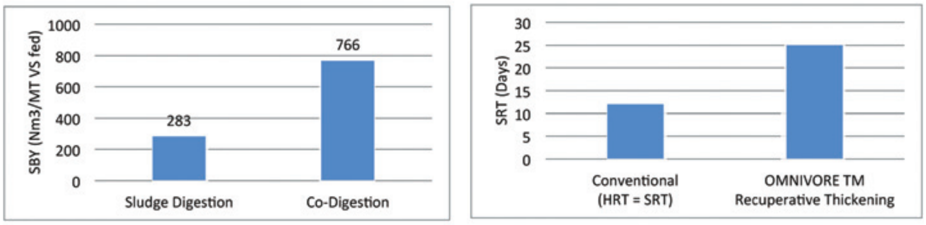
Figure 1. Anaergia's OMNIVORE^{TM} and OREX^{TM} systems are currently in use at PUB's Ulu Pandan Water Reclamation Plant in Singapore.

The food waste is first pre-treated with Anaergia's BIOREX^{TM} system, which extracts organics—separating them from non-organic contaminants and packaging such as plastics, metals and paper—for use in the digestion process. This extracted food waste is then combined with used water sludge utilising OMNIVORE^{TM}—an efficient digestion process also from Anaergia.

The results of the various tests performed as part of the operation have been promising. The OMNIVORE^{TM} co-digestion process showed stable long-term performance and produced more biogas than digesting sludge and food waste separately. Commercial food waste in Singapore contains high levels of starch, fat and protein, which results in high biogas potential. When used water sludge is co-digested with commercial food waste, volatile solid reduction of the sludge improved by 19% when compared to digesting sludge alone.

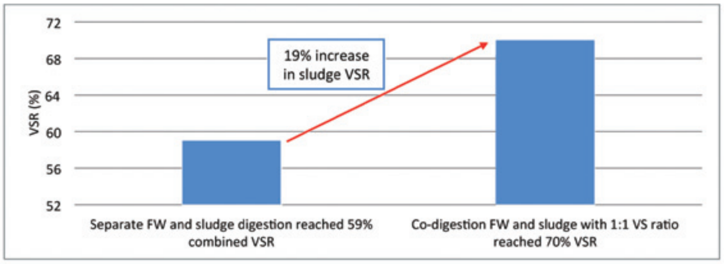
In fact, co-digestion using a volatile solids (VS) ratio of 1:1—equal parts of volatile solids from food waste and thickened sewage sludge—at an organic loading rate (OLR) of 3.2 kg VS/m^3 per day and solids retention time (SRT) of 25 days, resulted in a specific biogas yield (SBY) of about 2.7 times that of thickened sludge alone.

The data collected shows that with co-digestion, synergy between the used water and solid waste sector can be harnessed for increased energy production, which could enable wastewater treatment plants to shift from grid dependent consumers to energy neutral or energy-positive facilities. This brings the benefit of resilience as the plant can continue to run even at times of power cuts in the grid and is in line with PUB's technology roadmap to move towards a more energy sufficient WRP.



Comparison of specific biogas yields (SBY)

Comparison of specific solids retention times (SRT)



Comparison of volatile solids reduction (VSR) between separate and co-digestion operation

Figure 2. Graphs detailing the comparative performance of sludge digestion against co-digestion with food waste.

Improving water reclamation efficiency with a novel A-B process

Enhancing energy recovery and minimising sludge production in water reclamation processes using anaerobic ammonia oxidation (anammox), reverse osmosis and/or other innovative nutrients removal/recovery options

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The conventional activated sludge (CAS) process – which uses aerobic micro-organisms to oxidize organic matters in used water and produce sludge as a by-product – has been a core technology for used water treatment for more than 100 years. While the CAS process has been optimised over the years, this process may have reached its limit of being able to cope with the increased demand for environmental sustainability in used water treatment. Therefore new processes, designed for greater energy efficiency and recovery, as well as minimised sludge production are required.

A team at the Nanyang Technological University (NTU) is collaborating with SUEZ Water Technologies & Solutions and PUB to devise a novel A-B process for more sustainable used water reclamation. The novel A-B process configuration is primarily designed for enhanced energy recovery at the A-stage while the B-stage focuses on the energy-efficient nutrients removal/recovery. A 60 m^3/day demonstration system based on this novel A-B process is currently being trialled at PUB's Ulu Pandan Water Reclamation Plant.

During the A-stage, an anaerobic membrane bioreactor (AnMBR) is used to produce biogas with minimal generation of waste sludge. Unlike a traditional CAS system, organic matter in the used water is directly converted to biomethane in the AnMBR. This produces less sludge due to the low growth yield of anaerobic bacteria.

The effluent from the A-stage is then sent for nitrogen removal in the B-stage, where two methods are being tested: the first based on a step-feed mainstream anammox-MBR, and the second based on electrodialysis reversal (EDR). In both systems, the output water is fed into the reverse osmosis units to produce high-grade reclaimed water.

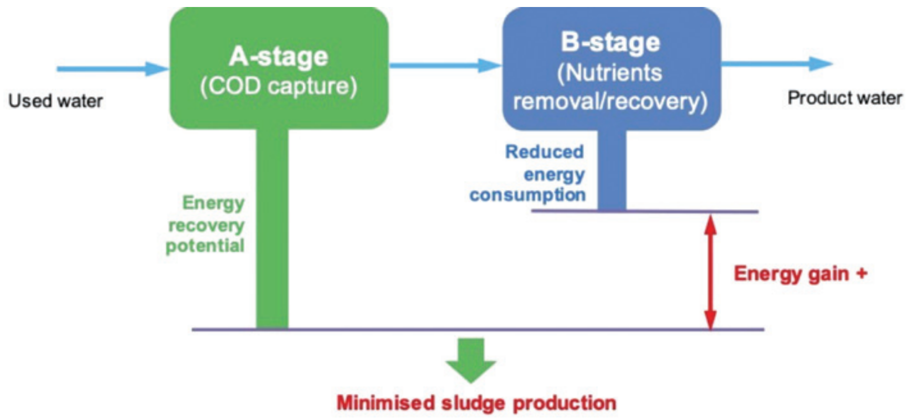

Figure 1. Overview of the Novel A-B process.

The first B-stage method uses anammox bacteria to anaerobically oxidise ammonium into nitrogen gas. Compared to conventional nitrification-denitrification method, this process could theoretically reduce oxygen and chemical oxygen demand (COD) by 60% and 90%, while reducing biosludge generation by up to 75% respectively.

The second method for the B-stage involves the use of an EDR system downstream of the AnBMR. This method also results in a reduction in both ammonia levels and the amount of total dissolved solids (TDS). A decrease in TDS enables more efficient operation of the RO filtration unit, which in turn translates into an energy saving of 0.08 kWh/m^3.

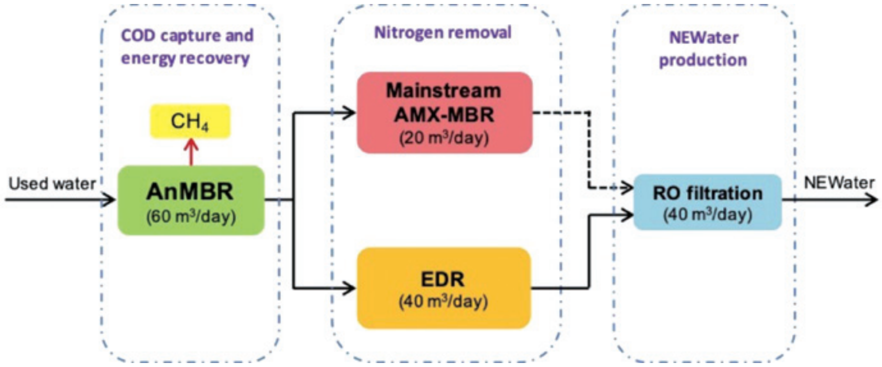

Figure 2. The Novel A-B processes.

The results of the trials indicate that both treatment options in the novel A-B process can offer a highly feasible engineering approach for cost-effective and energy-efficient used water reclamation promoting environmental and economic sustainability.

WATER QUALITY & SECURITY

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.

Diving deep into the issue of algal blooms with artificial intelligence

Integrating deep-learning algorithms, advanced automation systems and expert knowledge to revolutionise algae monitoring by enabling large-scale, high-frequency monitoring while improving accuracy, consistency and efficiency

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Singapore's water supply relies on reservoirs which are vulnerable to algal blooms, especially if not monitored closely. Algal blooms disrupt the natural balance of the aquatic ecosystem and may release harmful toxins into the water supply, affecting not only humans but the wider environment. With the rise of algal blooms observed in water bodies all around the world, early warning systems that enable pre-emptive measures to be implemented in a timely and appropriate manner to minimise impact become increasingly crucial. Such systems rely on the ability to perform regular monitoring for early detection of algal blooms.

Traditionally, efforts to research, monitor and curb algal blooms are labour-intensive and time-consuming. This is exacerbated by the shortage of professionals who can identify and monitor diverse microorganisms such as phytoplankton or planktonic algae.

To address this issue, PUB, in collaboration with long-term partners Zweec Analytics and Yangtze River Valley Water Environment Monitoring Center, have harnessed the power of deep learning to develop an artificial intelligence-based, automated recognition and counting system. Supported by microscopic image scanning, image processing and an expert-knowledge-based algorithm, the system can quickly and efficiently process sample batches and identify algal cells to determine phytoplankton numbers in water bodies.

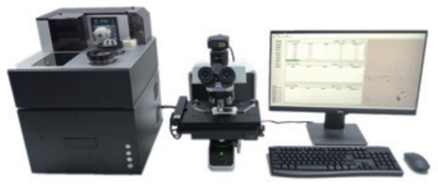

Figure 1. A photo of the automated phytoplankton monitoring system based on deep learning. It consists of a batch sample feeder and controller, a scanning digital microscope and a computer with the plankton identification software.

Liquid samples are fed into a digital microscope connected to a system that captures multiple fields of view and creates images of the phytoplankton, which are then identified by the plankton identification software. The algal cells are counted in real time by the algorithm, as shown in Figure 2. To date, the research team has used over 30,000 images of algae taken from water bodies in Singapore and the Yangtze River basin to train the system. During testing, the system achieved a high rate of recognition and counting accuracy – its counting results were matched against human experts – as illustrated in Figure 3.

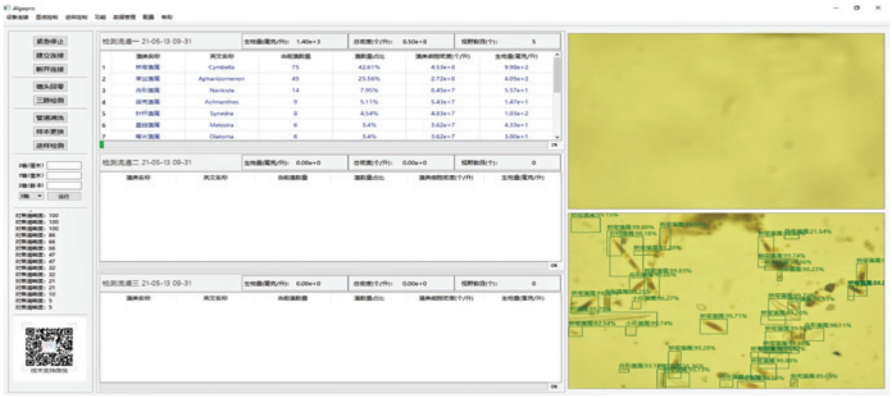

Figure 2. The algal cells of different genera, shown on the right side of the user interface, were recognised and counted in real time by the deep-learning-based algorithm and added to the table on the left.

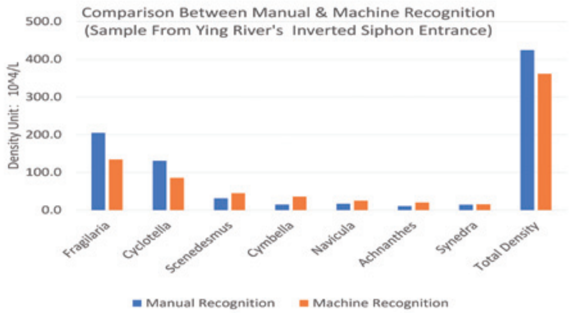

Figure 3. Comparison of the system's machine recognition results with manual recognition performed by a human expert for a field algae sample.

By training the software to accurately and automatically identify the different types of phytoplankton, monitoring of water samples can be done on a much larger scale and higher frequency. This represents a revolutionary breakthrough in smart water quality management. The accelerated and streamlined algae monitoring process also allows for more consistent implementation and analysis over time and across sites.

The research team is currently working to improve the system by further developing the algorithm and increasing the data size and images available in the database. This would facilitate a more robust and precise identification process that will help predict potential instances of algal blooms before they negatively impact the aquatic environment. The research team aims to roll out this promising monitoring system across Southeast Asia soon, and eventually, the rest of the world.

Cost-effective biomonitoring of reservoir water quality with environmental DNA

Updating water quality index for reservoir biomonitoring using water environmental DNA (eDNA)

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Biomonitoring of aquatic macroinvertebrate provides a more holistic temporal view of water quality as their abundances can be affected by changes in the water condition. Biomonitoring examines the communities of macroinvertebrates that inhabit a water body, and the information is subsequently used for biotic index calculation. These indices are established based on the tolerances of macroinvertebrates to pollution—whether the water allows the more sensitive species to survive. The use of such indices provides a systematic and consistent interpretation of water quality.

The Benthic Quality Index for Singapore Reservoirs (BQI_{SING}) was developed in 2008 as a result of a collaboration between PUB and the Tropical Marine Science Institute, National University of Singapore (NUS). This index is based on data-derived tolerance of local taxa (in this case macroinvertebrates) to stressors (water pollutants). The current method relies on sampling for macroinvertebrates in the reservoirs, which is highly resource intensive. Tasks include setting up sampling colonisers on the reservoir beds, collecting the macroinvertebrates, sorting them based on morphology, before counting and recording the numbers for each group.

In order to streamline the biomonitoring process, a team of researchers led by Prof Rudolf Meier and Dr Sujatha Narayanan Kutty from NUS are collaborating with PUB, to explore the use of a DNA-based method for biomonitoring as well as water samples as a replacement for sampling of macroinvertebrates. In this DNA-based method, only samples of water from the reservoir are needed to extract DNA present in it. The extracted DNA is subsequently amplified for the cytochrome oxidase I (COI) barcode marker, sequenced and analysed for species identification.

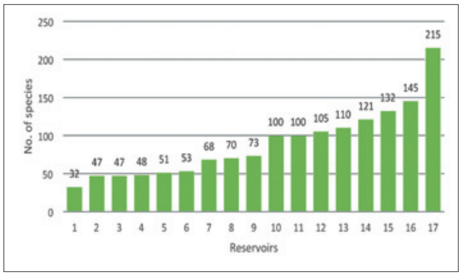


Figure 1. Number of species detected in one monthly water sample across 17 reservoirs.

As species communities in reservoir waters have yet to be thoroughly documented, the researchers need to first establish a baseline for the eDNA data of these biological communities. Water samples have been collected from all 17 reservoirs in Singapore and put through the DNA analysis workflow. The sampling process involved collecting water in 50 ml tubes with a scoop action from individual reservoirs. Multiple samples were taken to account for spatial differences, and samples were collected monthly for a year from selected reservoirs to account for temporal changes. Through this process, the research team has been able to identify between 32 to 215 species in the water samples from the different reservoirs.

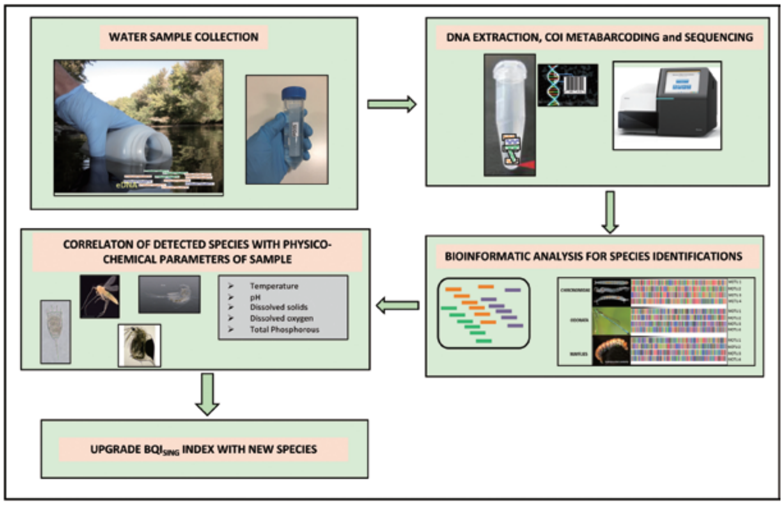
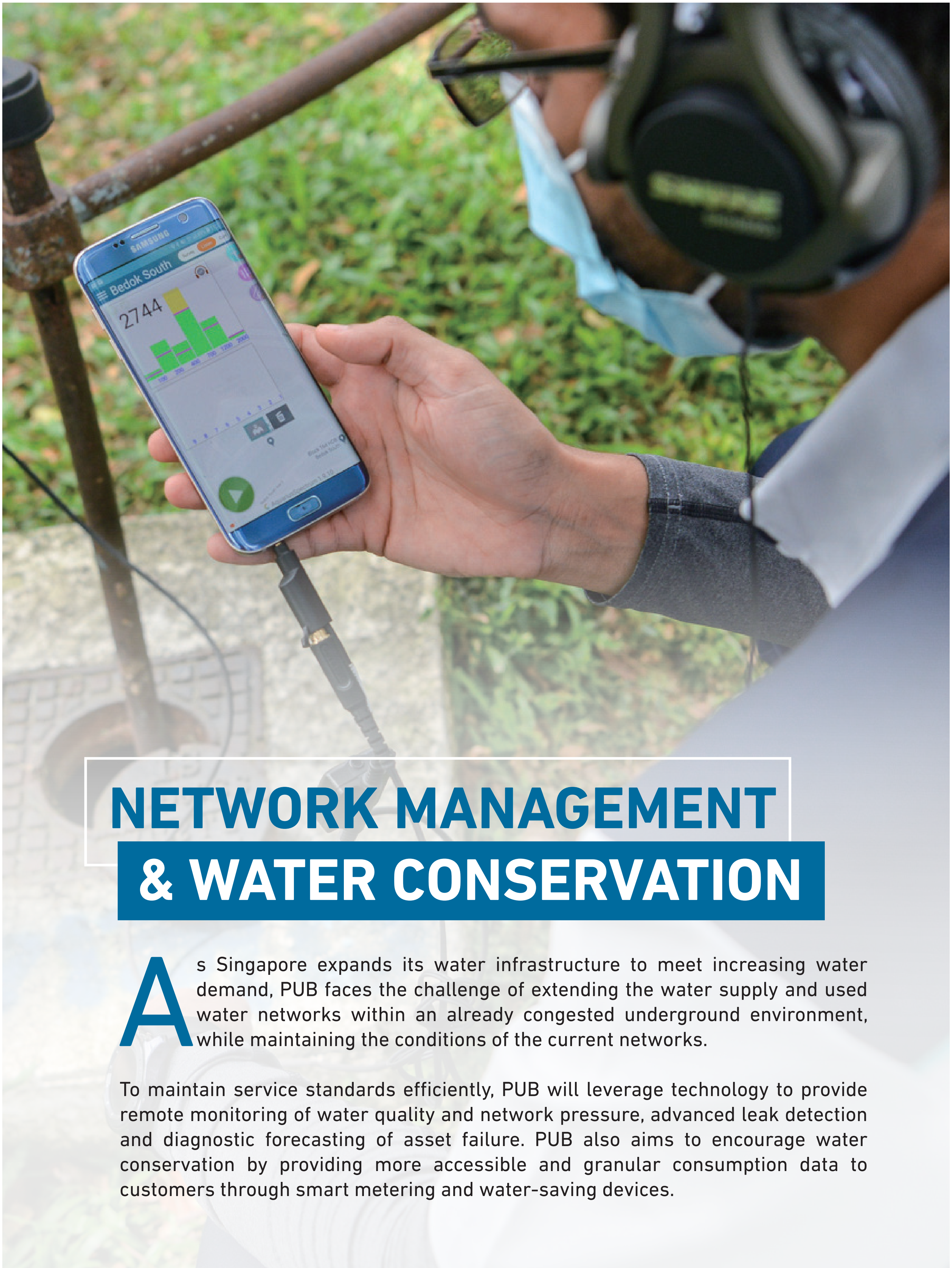


Figure 2. Steps in the process to update the BQI_{SING} index to enable use of eDNA for biomonitoring.

These studies have shown that there is an abundance of zooplankton species in the reservoir water's eDNA. As such, using zooplankton as indicator taxa has advantages over using macroinvertebrates, in particular, it allows for ease of collection and homogeneity of distribution throughout the water body. To move away from the time-consuming method of biomonitoring based on sampling for macroinvertebrates, the team is analysing the water samples to find correlations between the detected species and the physico-chemical parameters—such as pH levels, dissolved solids, dissolved oxygen and total phosphorous—in the water. The analysis will help to identify potential bioindicator groups that can then be included in the BQI_{SING} index.

With an updated BQI_{SING} index, PUB will be able to use eDNA for biomonitoring. Subsequently, PUB will only need to analyse the DNA of bioindicators in collected water samples, and match them against species in the index for a water quality assessment. Once an eDNA based workflow has been optimised, PUB will be able to replace the labour-intensive bulk macroinvertebrate sampling with regular analysis of water samples.



NETWORK MANAGEMENT & WATER CONSERVATION

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.

Incorporation of behavioural elements to enhance communications

Testing the effect of using behavioural insights to influence consumer behaviour and enhance engagement for water conservation

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In 2019, Singapore National Water Agency PUB, SUEZ—a global player in environmental services, and Behavioural Insights Team (BIT)—a social impact consultancy firm, collaborated on a behavioural science study aimed at decreasing household water consumption and reducing the amount of time households take to fix leaks. Two randomised control trials (RCTs) were implemented under this study to look at the use of behavioural principles to influence consumer behaviours. One of them involved the use of behavioural insights in recruitment letters to encourage the download of a smart meter mobile application, and the other involved the use of behavioural insights in the smart meter mobile application and leak notice letters to get consumers to use less water and fix their leaks promptly.

The trial comprised 1,058 households that met the technical requirements for installing the smart water meters in a designated estate. The selection of the estate and households is meant to be representative of the general Singapore population as much as possible.

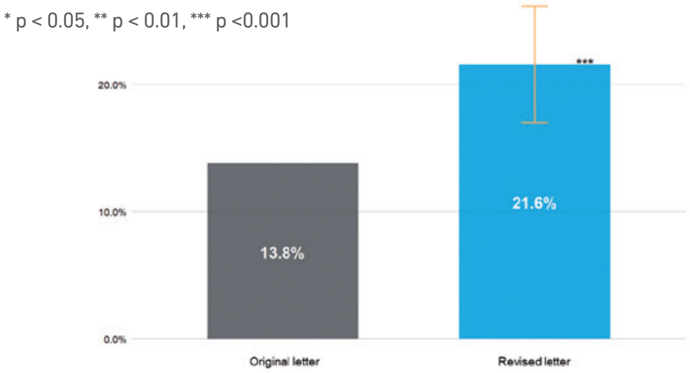
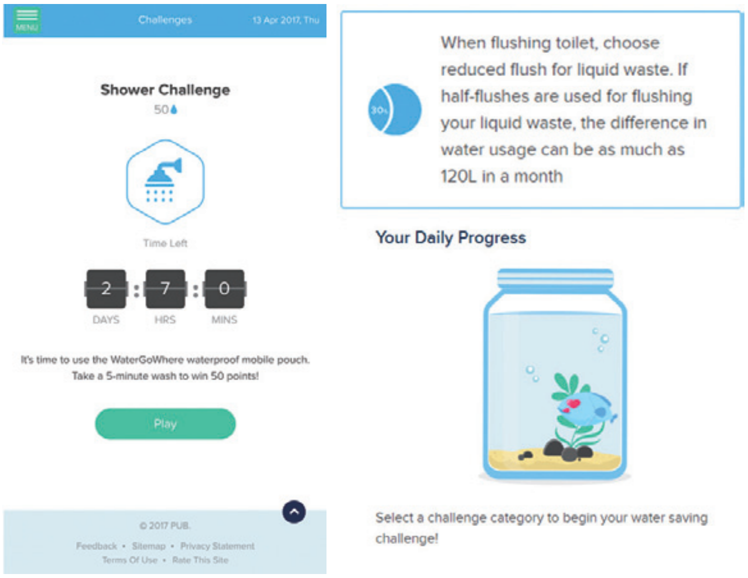


Figure 1. Percentage of households that registered on the app based on the two versions of letter.

In the RCT to encourage usage of a smart meter app, recruitment letters were sent out to invite households to download the app. Half of the households were sent the original letter which was a typical recruitment letter providing basic information and instructions.



It's time to use the WaterGoWhere waterproof mobile pouch. Take a 5-minute wash to win 50 points!

When flushing toilet, choose reduced flush for liquid waste. If half-flushes are used for flushing your liquid waste, the difference in water usage can be as much as 120L in a month

Your Daily Progress

Select a challenge category to begin your water saving challenge!

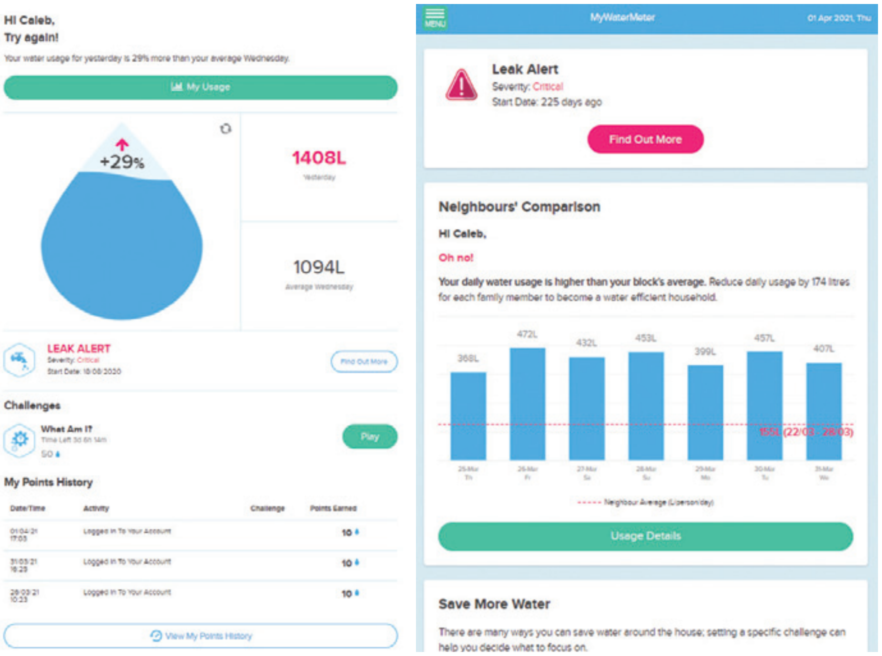
Figure 2. Examples of challenges suggested by the WaterGoWhere (WGW) to encourage water-saving behaviour.

The other half were sent a revised letter, incorporating behavioural principles. In addition to the basic information, the revised letter included a personalised water usage chart for each residential unit, a testimonial from an active app user, a checklist of steps to download, and a deadline to register which was highlighted in the subject. These revisions were designed to encourage users to download the app.

Results show that 7.8 percentage points more households who received the revised letter signed up for the app. This difference is statistically significant, thus prompting further research and action in this area.

In the second RCT, half of the households were offered the WaterGoWhere (WGW) app, while the other half were offered the MyWaterMeter (MWM) app. The offers were independent of the version of recruitment letter they had received. Compared to the WGW app, the MWM app is enhanced with behaviourally-informed features—for instance a graph comparing the household's water consumption against their neighbours', a goal-setting feature to encourage water-saving behaviour, a list of nearby plumbers and so on.

Alongside this, households with leaks were sent a letter to encourage them to fix their leaks promptly. Households that were offered WGW received the original leak letter, while households that were offered MWM received the revised leak letter. The revised leak letter included elements to encourage action: (1) a to-do list instead of a set of instructions like in the original leak letter, (2) additional information on how little time is required to fix the leak, and (3) follow-up action from PUB to check that the leak has been fixed.



Hi Caleb,
Try again!

Your water usage for yesterday is 29% more than your average Wednesday.

LEAK ALERT
Severity: Critical
Start Date: 18/08/2020

Challenges

What Am I?
Time Left 3d 6h 14m
50

My Points History

Date/Time	Activity	Challenge	Points Earned
01/04/21 17:05	Logged In To Your Account		10
31/03/21 16:29	Logged In To Your Account		10
28/03/21 10:23	Logged In To Your Account		10

Leak Alert
Severity: Critical
Start Date: 225 days ago

Neighbours' Comparison

Hi Caleb,

Oh no!

Your daily water usage is higher than your block's average. Reduce daily usage by 174 litres for each family member to become a water efficient household.

Save More Water

There are many ways you can save water around the house; setting a specific challenge can help you decide what to focus on.

Figure 3. MyWaterMeter (MWM) interface provides detailed information on usage patterns and a status indicator for leaks.

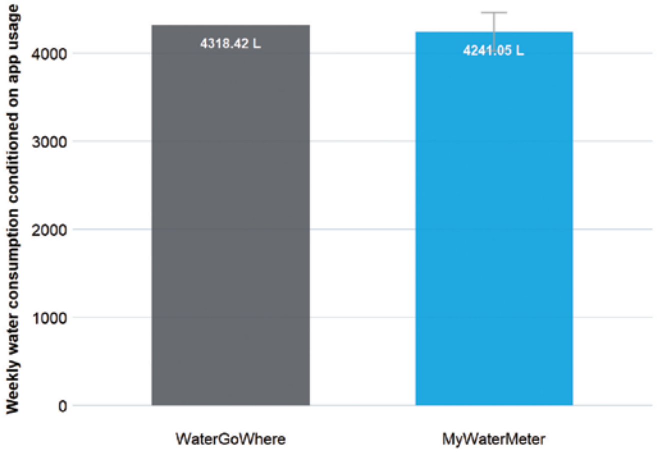


Figure 4. Weekly water consumption for households using respective apps WGW and MWM.

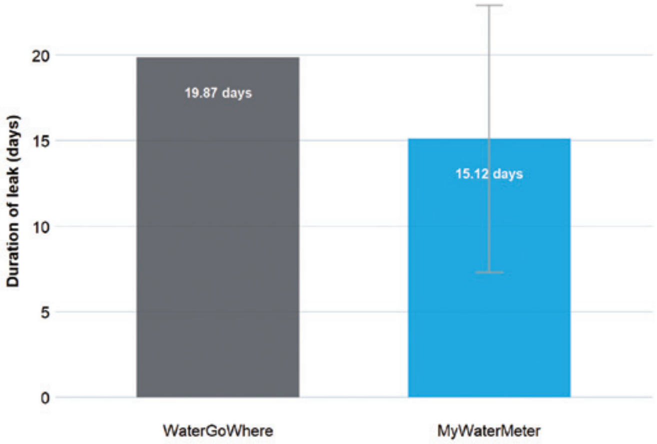


Figure 5. Average duration of leaks in households using respective apps WGW and MWM.

Results show that households offered MWM with the revised leak letter used approximately 2.3 percentage points less water and repaired their leaks 4.95 days faster than households offered WGW. While neither finding is statistically significant, the resulting effects in encouraging water conservation are nevertheless meaningful, given that MWM was tested against an active control (WGW). Additionally, we also calculated the cost savings associated with this difference; on average, leaks in the MWM group cost $7.62 and leaks in the WGW group cost $11.34. Using the MWM app saved $3.72 per leak on average.

The results of these trials show that the incorporation of behavioural elements into communications regarding the smart water meter app can have a positive impact on the upcoming national rollout. In identifying barriers that users have, future efforts can focus on overcoming these barriers, while more observed or deduced behavioural insights should continue to be tested using larger sample sizes.

Reducing cost and improving efficiency of water network monitoring with IoT

Increasing the operational efficiency and asset reliability of installed microbial electrochemical sensor (MES) units for real-time heavy metal monitoring in the used water network through the use of an IoT platform and web-based dashboard

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Early detection of toxic compounds in high concentrations in factories' discharge enables prompt actions to be taken to stop the toxic discharge at sources, mitigating the risk for potentially harmful consequences. Real-time water-quality monitoring sensors can facilitate the detection of dangerous, hazardous and toxic wastes, and help operators identify those responsible for illegal or accidental discharge into the sewers. This safeguards the used water treatment processes for NEWater production in Singapore, and the safety and health of workers maintaining the sewerage network.

PUB has worked with the National University of Singapore (NUS) and its spin-off company EnvironSens, to develop MES, known as the Integrated Intelligent Biosensor (I2BioS) and to trial its use at factories dealing with regulated parameters (e.g. heavy metals and cyanide) which can possess toxicity. The I2BioS System provides continuous monitoring system of toxicity in factories' discharge and presents the current status online via a web interface. Water quality and toxicity levels are tracked 24/7 in real-time, with SMS alerts sent to the appointed personnel should any excursion events be detected. When the alert is triggered, the system will also collect the toxic sample automatically.

At present, one hundred units of the I2BioS have been installed by PUB at factories to detect the presence of heavy metals and cyanide in used water. These are mainly located in the Western part of Singapore (see Figure 2), where there is a higher concentration of heavy industries. I2BioSs transmit the current status of the effluent via RS485 protocol to narrow-band IoT (NB-IoT) devices that receive and consolidate data to be transmitted to the web dashboard. The use of NB-IoT keeps the power consumption of this set up low, while using limited spectrum. This enables the I2BioS to have the capacity to support a large number of connections, making this solution scalable well beyond its current hundred-unit set up.

Figure 1. MES installed with IoT transmitter.

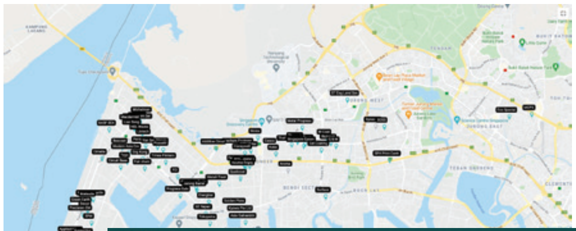

Figure 2. Map showing location of each installed MES unit. Users are able to double click on the location to view detailed information of that installation (as illustrated in Figure 3).

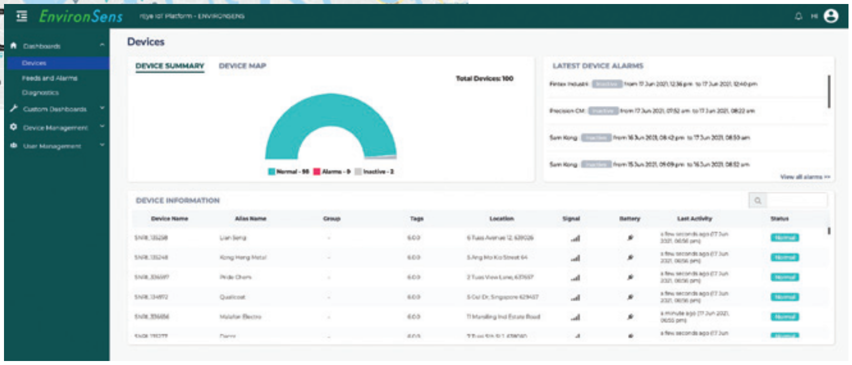

Figure 3. IoT-based Web Dashboard showing device-level information.

EnvironSens has a web dashboard which presents a range of related data that can help improve process efficiency, asset utilisation and productivity. The IoT-based web dashboard helps to reduce operational cost through real-time tracking of the installed sensors. Users can leverage data analytics to gain real-time insights, and help them make smarter and more timely decisions.

The developed web-based dashboard allows the user to view a map (see Figure 2) showing the status of the installed units throughout Singapore, and allows access to their individual maintenance records (see Figure 3), trigger records and other information. It is programmed to send alerts to the user's email and/or mobile phones through SMS, when an alarm is triggered by an installed unit.

The convergence of real-time data, device management, device tracking, alarms, maintenance records, and online reports not only provides a way to deter factories from carrying out illegal discharge of heavy metals and cyanide in the used water network more proactively, it also allows users to manage the assets and devices in the network efficiently which reduces overall operational and manpower cost. In addition, the deployment of MES units has deterred the companies from discharging illegally. As a result, the number of illegal discharges affecting nitrification process of WRPs has reduced significantly after the deployment of MES units.

DIGITALISATION

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. PUB is exploring technologies on robotics, sensors and network communications, system automation, digital twin and AI that could help to maximise productivity and enhance operational reliability and security within the water loop.

Unmanned drone for reservoir management

Digital pump monitors make a splash with potentially massive energy savings

Implementation of a new pump monitoring system that enables more efficient energy consumption and better intelligence towards improved asset management strategies

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Modern society's increasing thirst for water demands cutting-edge technology to increase the efficiency and sustainability of water resources management. By integrating digitalisation, PUB is enhancing its water management operations and processes for higher optimisation and resilience—as exemplified by the water distribution system. Pumps are a key part of water distribution systems, and any malfunctions are costly as repair works require shutdowns. Therefore, it is imperative to the entire system to ensure that the pumps are in good condition and functioning properly. Instead of relying on traditional monitoring methods which deliver variable results, are subjective and time consuming, PUB is moving towards making key decisions based on meaningful data. To collect the necessary data, PUB has tested an innovative, data-driven system for monitoring pump performance.

In collaboration with Riventa, PUB has introduced the FREEFLOW system, an IIoT (Industrial Internet of Things) digital thermodynamic pump efficiency monitoring system, at Queensway Booster Station to monitor the status and performance of the pumps in real-time. The station runs on a specific operations regime based on time and the stock level of the service reservoir. Operators monitor the three power specific pumps based on operational requirements while balancing the running hours between them. The integration of the FREEFLOW system enables the precise measurement of both water temperature and pressure at any given moment. Real-time data is then made available to operators via Riventa's HydraNet cloud platform.

Figure 1. The Riventa FREEFLOW monitoring device.

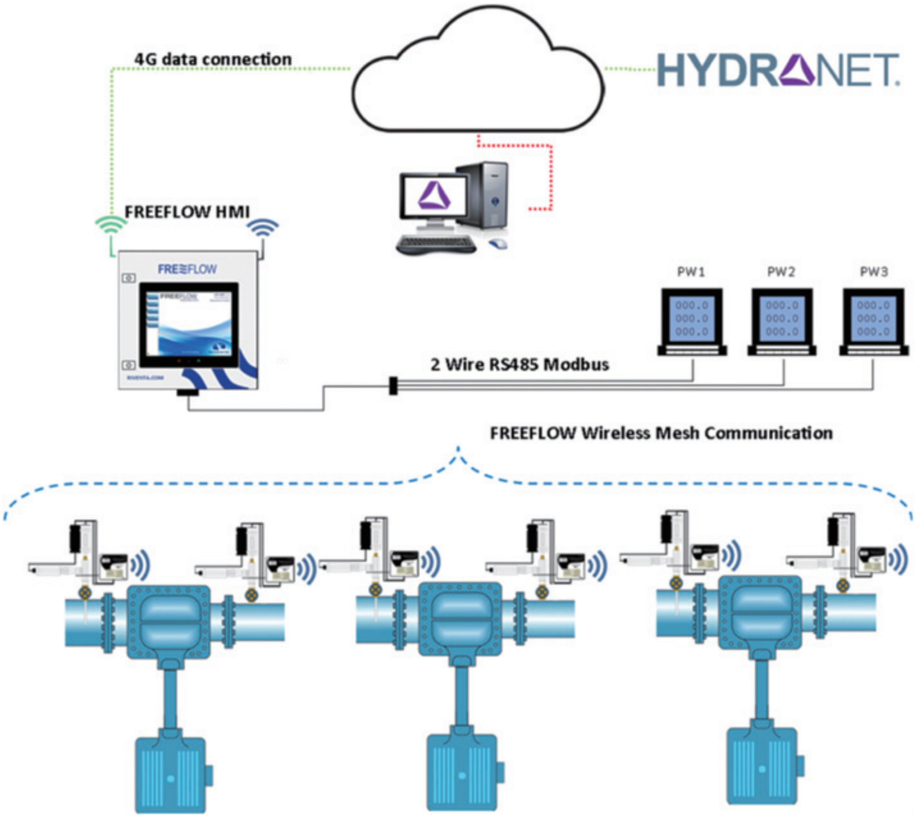

Figure 2. Data transmission landscape in the Riventa FREEFLOW system, from pump to operator.

Since its implementation, the FREEFLOW system has successfully delivered accurate, real-time information on each individual pump's performance. Such data provide insights to the efficiency of the pumping station and can highlight any potential issues that may arise. Data gleaned from the Riventa system have been used to devise solutions that further optimise operating conditions for the pumping system. This includes prioritising the use of the most efficient pump combinations, activating their inverters, reducing the flow rate set point, and increasing operational duration to minimise pump head requirement. Due to these optimisations, pumping costs of up to 29% can be reduced. Further insights are also helping to improve the hydraulic efficiency of the pumping station.

Using AI to help monitor and control water treatment quality

Utilise AI to perform advanced fault prediction and improve operational efficiency in water treatment plants

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To improve the water treatment process control in water treatment plants, consultancy firm Surbana Jurong has developed an artificial intelligence (AI) integrated Smart Supervisory Control and Data Acquisition (SCADA) system. This system is designed to perform advanced fault prediction in order to improve the operational efficiency of water treatment plants.

A Smart SCADA system has been deployed at a PUB water treatment plant for testing and validation. In this setup, the Smart SCADA system works in conjunction with existing SCADA and PLC systems in the treatment plant to function as a decision-support system. AI algorithms developed based on a series of models train the system to monitor the water treatment processes and identify when they deviate from the norm. A large volume of data can also be securely fed into the AI system passing through a series of data diodes and firewalls, in order to predict the quality of the treated water.

By examining the complex interactions and relationships between a large set of parameters, the smart SCADA system predicts potential issues and determines their impact on the water quality before a fault occurs. The type of faults that the system can detect include abnormal measurements from instrument outputs, defective pumps, deviations from process parameters and set-points. The AI algorithm can also localise the issue within the plant.

Once a potential fault has been detected, the smart SCADA system alerts the human operators of the anomalies so that prompt action can be taken to prevent a fault occurrence. It can also carry out informed troubleshooting in an optimal manner, identifying and rectifying issues, sometimes before they even occur. This proactive approach to operational issues allows them to be addressed with appropriate speed and precision, which in turn reduces the occurrence of false alarms and minimises the need for plant shutdowns.

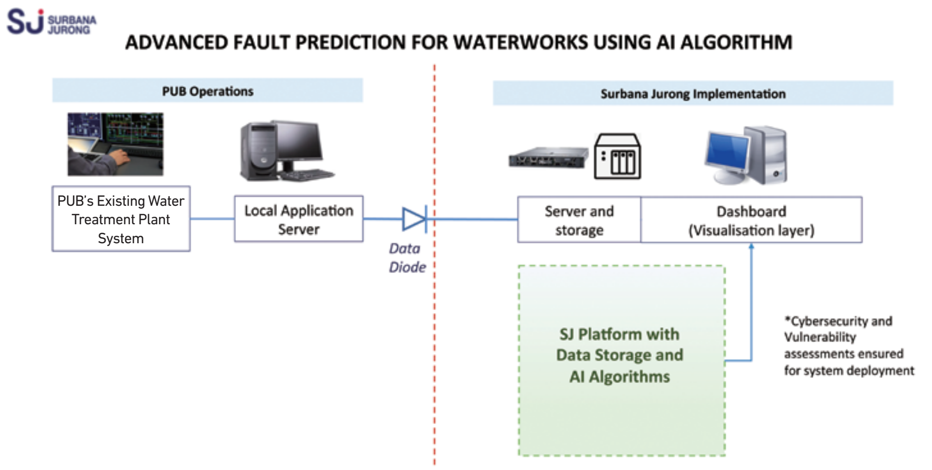

Figure 1. Schematic showing how the Smart SCADA system is integrated with PUB's existing treatment plant systems.

Figure 2. Plant staff can monitor operations and view details of potential issues picked out by the AI algorithm remotely via a dashboard that is customisable by the operator.

Other ways in which this Smart SCADA system can improve productivity in water treatment plant is to reduce wastage. Water affected by deviations in the process continues to flow to subsequent treatment stages, thus resulting in water which does not meet PUB's required specifications. When this happens, the water needs to be discharged and re-purified. Identifying process anomalies and making timely rectifications would reduce the need for reprocessing substandard water. This not only saves energy, money and time, but also helps to maintain constant quality of the output water.

The machine learning models developed in this pilot programme can easily be scaled and deployed in other water treatment facilities for both municipal and industrial water supplies.

WASTE REDUCTION & RESOURCE RECOVERY

PUB's two major waste streams, incinerated ash from used water sludge and waterworks sludge, currently constitute to 6% of the total waste sent to Semakau Landfill. With projections that sludge generation is expected to double in tandem with water demand by 2060 and that Semakau Landfill will reach its full capacity by 2035, the need to look into reducing our sludge generation along with extracting useful materials from sludge has become pertinent. The waste reduction and resource recovery domain is set up to contribute towards Singapore's ambition of a zero-waste nation and drive for a circular economy.

Waste-to-Energy Research Facility by NTU and NEA

From NEWater to NEWSand — converting sludge to green construction material sustainably

Exploring and developing sustainable processes using high-temperature slagging gasification to convert sludge and ash into green construction materials for Singapore

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Water reclamation plants (WRPs) in Singapore currently generate approximately 300,000 tonnes of wet sewage sludge every year. This sludge is then incinerated at two sludge incineration facilities (SIFs) and the resultant ashes — approximately 30,000 tonnes every year — are sent to Singapore's only operating landfill site on Pulau Semakau. A further 15,000 tonnes per year of dewatered sludge from the freshwater treatment process at waterworks (WWs) are also disposed at the Semakau Landfill without further treatment. At this rate, concurrently with the disposal of other non-incinerable wastes and ashes from the incineration of municipal solid waste (MSW), the site is projected to be full by 2035.

The Waste-to-Energy Research Facility (WTERF) launched jointly by Nanyang Technological University, Singapore (NTU Singapore) and the National Environment Agency (NEA) is currently researching alternative thermal treatment technologies for the sludge and ash. The research is centred around high-temperature slagging and co-gasification processes that convert diverse waste streams — from (1) MSW, (2) waterworks sludge, (3) sewage sludge and (4) incineration ash — into high quality slag.

Co-gasification of the four waste streams in different combinations and loading levels into the gasifier were tested, and the resulting slag were assessed for their suitability as sustainable construction materials. Operating at temperatures up to 1,600˚C — much higher than conventional incinerators which typically operate at around 850˚C — the processed slag is transformed to have different properties. In total, 13 different types of sludge-derived slag were generated (Figure 1).

The slag generated has the potential for use as green construction material, with possible applications including structural and non-structural applications in concrete production, land reclamation and coastal protection amongst others. Preliminary tests show that the sludge-derived slag has great re-utilisation potential due to its particle size distribution being comparable to sand. When measured against the EN-12457-1/2:2002 standards, the slag samples demonstrated very low leaching of heavy metals and meet the strictest EU landfill waste acceptance criteria for inert waste materials. Mortar created using slag instead of sand as the fine aggregate has also yielded satisfactory compressive strength in laboratory tests.

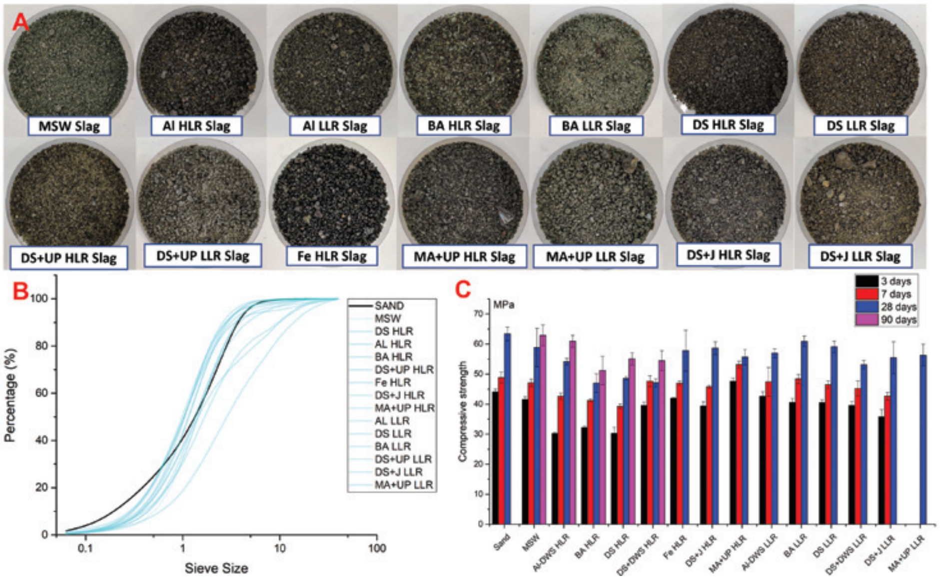

Figure 1. Photos illustrating different types of slag generated from the co-gasification research at the WTERF. The chart below shows the particle size distribution analysis of slag and sand, and the test results for compressive strength of mortar produced from using this slag, which replaces sand as the fine aggregate. The testing is currently ongoing.

Turning sludge into a material source for the construction sector supports Singapore's efforts towards a circular economy and will also help extend the lifespan of the Semakau Landfill with less waste being sent there. Since the ultimate aim of this project is to provide scientifically informed recommendations for sustainable sludge treatment processes, aspects such as optimal production for large-scale usage, durability and utilisation methodologies for specific applications of the sludge-derived slag are being developed concurrently. In terms of energy recovery, the efficient use of combustible syngas — another by-product from the processes — is also being explored at WTERF.

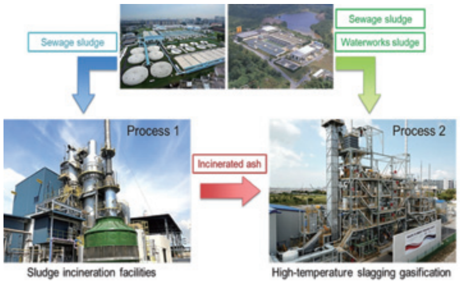

Figure 2. An overview of the thermal treatment processes that go into creating NEWSand from a combination of different waste streams.

Could biochar nurture Singapore’s Urban Farming future?

Development of uses for biochar—a by-product from pyrolysing sewage sludge

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Approximately 300,000 tonnes of sewage sludge is generated in Singapore annually. After dewatering, the sludge is incinerated and the residual ash is then stored at Singapore’s only landfill at Semakau. However, sewage sludge contains considerable amounts of nutrients and micronutrients such as phosphorus, nitrogen, and zinc, which have the potential to be beneficially repurposed. With the prospect of high yields, there is a need to find ways of utilising such sludge to turn it into a sustainable resource.

Pyrolysis—the process of heating biomass in an oxygen-limited environment—decreases the volume of sludge by more than half and produces biochar as a by-product. The biochar can be added to soil to improve its water and nutrient retention capabilities and increase its pH. Biochar also has potential as an odour control medium which is useful for Water Reclamation Plants (WRPs). Hence, pyrolysis serves as an efficient solution for sludge management by reducing its volume, and the resulting biochar provides a cost-efficient and environmentally sustainable resource to support urban farming as well as odour control applications.

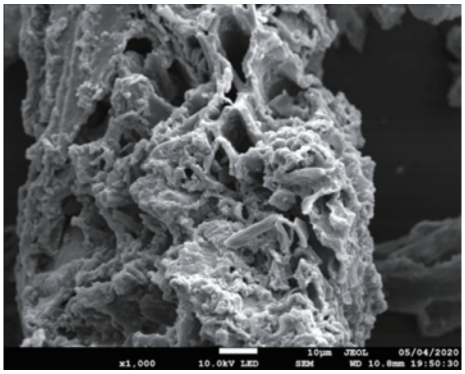

Figure 1. Scanning electron microscope image of biochar produced from the pyrolysis of sludge.

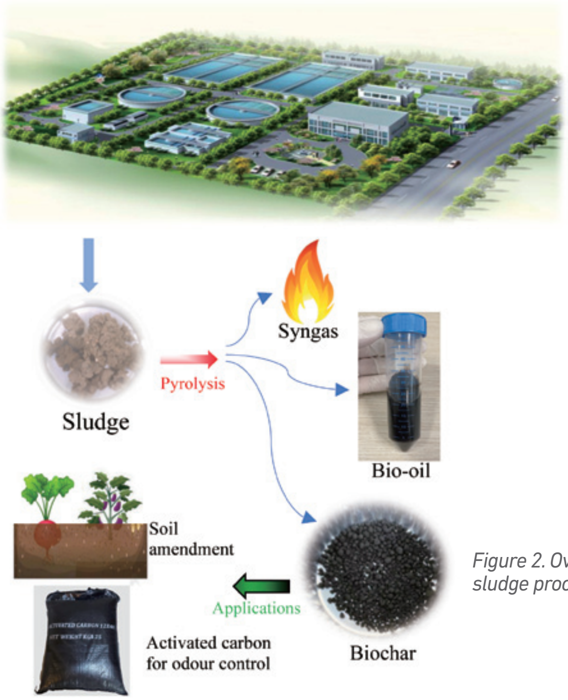

Figure 2. Overview of sewage sludge processing and utilisation.

However, before implementing biochar on a large scale, the issue of consistency in its properties needs to be addressed. Researchers from NTU are currently exploring solutions to these issues in partnership with PUB. Studies have shown that the characteristics and product yield of biochar can be influenced by the feedstock type and composition and pyrolysis process conditions. To optimise the structure of biochar (see Figure 1) to produce porous and fine-grained structures, sludge from different WRPs is pyrolysed under different conditions and then analysed for its usability.

Another concern is the presence of heavy metals (HMs) and other chemical compounds that could leach from the biochar even after it has been pyrolysed. Potential bioaccumulation of these compounds in plants could have health risks. However, based on the current tests, the results have so far been promising: the HMs content meet International Biochar Initiative (IBI) Biochar Standards for land application and the rate of HM leaching is much lower than the US EPA standard. The team is also assessing the safety of biochar use in agriculture in accordance with Sewage Sludge Directive 86/278/EEC, monitoring and analysing the properties of plants and the biochar-soil mixture in on-going pot experiments.

While the repurposing of this nutrient-rich by-product for urban farming will help to divert sludge away from landfill, other uses for this resource will no doubt be welcomed in land-scarce Singapore, as the volume required by agricultural needs may still be limited for the time being. Hence, the effectiveness of biochar in removing H_2S from the air is being tested in studies that are looking to have biochar replace activated carbon as an odour control medium for WRPs.

Research into extracting value from waste through innovative processes and novel applications will close the waste loop, support food security through agricultural independence and create a new resource stream for industry.

LIST OF ABBREVIATIONS, ACRONYMS, SYMBOLS & UNITS

Acronyms & abbreviations

ABC	Active, Beautiful, Clean Waters
ABM	Aquaporin-based Membrane
AEBC	Advanced Environmental Biotechnology Centre
AI	Artificial Intelligence
AIT	Asian Institute of Technology
ANAMMOX	Anaerobic Ammonia Oxidation
AnMBR	Anaerobic Membrane Bioreactor
APC	Advanced Process Control
BIT	Behavioural Insights Team
BQI_{SING}	Benthic Quality Index for Singapore Reservoirs
BWRO	Brackish Water Reverse Osmosis
CAS	Conventional Activated Sludge
CCKWW	Choa Chu Kang Waterworks
CCTV	Closed-circuit Television
COD	Chemical Oxygen Demand
COI	Cytochrome Oxidase I
CQDs	Carbon Quantum Dots
CWRP	Changi Water Reclamation Plant
DI	Deionized Water
DLM	Domestic Liquids Modules
DTSS	Deep Tunnel Sewerage System
DUW	Domestic Used Water
DX	Digital Transformation
EDB	Economic Development Board
eDNA	Environmental DNA
EDR	Electrodialysis Reve rsal
ERD	Energy Recovery Device
ESG	Environmental. Social and Governance
EWTCOI	Environmental & Water Technology Centre of Innovation
H2i	Hydroinformatics Institute
HDB	Housing & Development Board
HMs	Heavy Metals
HRT	Hydraulic Retention Time
IBI	International Biochar Initiative
I2BioS	Integrated Intelligent Biosensor
IIoT	Industrial Internet of Things
ILM	Industrial Liquids Modules
IoT	Internet-of-Things
IUW	Industrial Used Water
IWMF	Integrated Waste Management Facility
IWSDF	Industrial Water Solutions Demonstration Fund
KICT	Korean Institute of Civil Engineering and Building Technology
KMEDP	Keppel Marina East Desalination Plant
LCA	Life-cycle Assessments
MBR	Membrane Bioreactors
MES	Micro-Electrochemical Sensor
MNCs	Multinational Corporation
MOFs	Metal-organic Frameworks
MRF	Materials Recovery Facility
MSW	Municipal Solid Waste
MWM	MyWaterMeter
NB-IoT	Narrow-band Internet-of-Things
NEA	National Environment Agency
NEWRI	Nanyang Environment and Water Research Institute
NParks	National Parks Board
NRF	National Research Foundation
NRP	National Recycling Programme
NTU	Nanyang Technological University
NUS	National University of Singapore
O&M	Operations and Maintenance
OLR	Organic Loading Rate
PLCs	Programmable Logic Controllers
PRO	Pressure Retarded Osmosis
PWCs	Public Waste Collectors
PUB	PUB, Singapore's National Water Agency
PV	Photovoltaic
PWP	Pure Water Permeability
R3C	Residues and Resource Reclamation Centre
R&D	Research & Development
RBC	Rotating Biological Contactors
RCTs	Randomised Control Trials
RFPs	Request-For-Proposals
RO	Reverse Osmosis
SBY	Specific Biogas Yield
SCADA	Supervisory Control and Data Acquisition
SEM	Scanning Electron Microscope
SERIS	Solar Energy Research Institute of Singapore
SG-MEM	Singapore Membrane Consortium
SgWX	Singapore Water Exchange
SIF	Sludge Incineration Facilities
SIWW	Singapore International Water Week
SJ	Surbana Jurong
SMEs	Small and Medium Enterprises
SRT	Solid Retention Time
START	Separation Technologies Applied Research & Translation
SWA	Singapore Water Association
SWRO	Seawater Reverse Osmosis
TDS	Total Dissolved Solids
TFC	Thin-film Composite
TFN	Thin-film Nanocomposite
TRL	Technology Readiness Level
TWRP	Tuas Water Reclamation Plant
UPWRP	Ulu Pandan Water Reclamation Plant
US EPA	United States Environmental Protection Agency
VS	Volatile Solids
VSR	Volatile Solids Reduction
WGW	WaterGoWhere
WRP	Water Reclamation Plant
WTE	Waste-to-energy
WTERF	Waste-to-energy Research Facility
WWs	Waterworks

Symbols & units

˚C	Degree Celsius
h	Hour
Ha	Hectare
kg	Kilogram
kWh/m^3	Kilowatt-hour per cubic meter
kWp	Kilowatt-peak
L	Litre
L/min	Litre per minute
LMH/bar	Litre per square meter per hour per bar
m	Meter
m^3	Cubic meter
m^3/day	Cubic meter per day
m^3/mth	Cubic meter per month
m/s	Meter per second
mgd	Million (imperial) gallons per day
min	Minute
ml	Millilitre
nm	Nanometer
ppm	Parts per million
tpd	Tonnes per day

PUB COLLABORATORS

Universities, research centres & international organisations

Advanced Environmental Biotechnology Centre	Singapore
Agency for Science, Technology and Research	Singapore
American Water Works Association	USA
Canadian Water Network	Canada
Centre for Environmental Sensing and Modeling	Singapore
Centre for Remote Imaging, Sensing and Processing	Singapore
Centre for Water and Environmental Biotechnology	Australia
Cooperative Research Centre for Water Sensitive Cities	Australia
Cranfield University	UK
Delft University of Technology	Netherlands
DHI-NTU Water and Environment Research Centre	Singapore
DSO National Laboratories	Singapore
Georgia Institute of Technology	USA
Global Water Research Coalition	International
Griffith University	Australia
Hyundai-NTU Urban System Center	Singapore
Imperial College London	UK
Institute of Environmental Science and Engineering	Singapore
International Desalination Association	USA
International Water Association	UK
International Water Resources Association	USA
KAUST Water Desalination and Reuse Center	Saudi Arabia
KWR Water 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
National Centre of Excellence in Desalination	Australia
National University of Singapore	Singapore
New Energy and Industrial Technology Development Organisation	Japan
Ngee Ann Polytechnic Centre of Innovation for Environmental & Water Technology	Singapore
NUS Environmental Research Institute	Singapore
Queensland Government	Australia
Sandia National Laboratories	USA
Singapore Centre on Environmental Life Sciences Engineering	Singapore
Singapore Membrane Technology Centre	Singapore
Singapore Polytechnic	Singapore
Singapore University of Technology and Design	Singapore
Singapore Water Association	Singapore
Singapore-MIT Alliance for Research and Technology	Singapore
Singapore-Peking-Oxford Research Enterprise	Singapore
Stanford University	USA
STOWA Foundation for Applied Water Research	Netherlands
SWELIA Association	France
Temasek Polytechnic	Singapore
The Commonwealth Scientific and Industrial Research Organisation	Australia
Toray Singapore Water Research Center	Singapore
Trent University	Canada
Tropical Marine Science Institute	Singapore
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Water Services Association of Australia	Australia
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