INNOVATION
IN WATER SINGAPORE

VOLUME 11 • JUNE 2019

Water 4.0

Riding the digital wave
in water research

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 ensure an efficient, adequate and sustainable supply of water.

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

Contents

Innovation in Water, Singapore

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

Acknowledgements

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

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

Editorial
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Statistics
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Design and production by purple circle design

WELCOME MESSAGE

Dear readers,

We are pleased to bring you the 11th edition of "Innovation in Water, Singapore", our annual chronicle of the significant research and developments in the water domain. This year, we are focusing on digital technologies that have the potential to transform water utilities around the world, and how PUB is transforming its operations into the Smart Utility of the future. In Singapore, our key mission is to provide a safe and sustainable supply of water. To do so, we must manage our water loop effectively and efficiently, keep the cost of water affordable, ensure that there is enough water for all and limit the impact of water-related events such as flash floods and prolonged dry spells. Digitalisation will play an increasingly important role in helping us deliver on these fronts.

A Smart PUB roadmap for intelligent water management in Singapore

Driven by growing water demand, rising operational costs, manpower constraints and new challenges like climate change, we intend to leverage digital solutions and smart technologies in PUB's operations. These include automation, artificial intelligence, big data and machine learning, to strengthen our operational resilience, productivity, safety and security.

We have charted our path forward in a Smart PUB Roadmap, and have shared more details about our plans and proposals, as well as our research projects with academia and industry partners, in this publication. For example, in recent years we have introduced new systems to improve our operations, including a three-radar network to refine our rainfall prediction capability, and a Catchment and Waterways Operations System to better coordinate our flood prevention efforts and provide earlier flash flood warnings to Singaporeans.

Towards a Smarter Work Future

At the same time, digitalisation is also about improving the daily lives of our water professionals, collaborators, stakeholders and our customers. This means empowering our staff with the knowledge and tools to do their work more easily and collaborate with their team mates more effectively; creating opportunities to develop technologies and better synergies between the different R&D and engineering communities; and improving our service delivery to the public who depend on water as a vital resource.

Looking ahead, we will also continue to invest in other innovations to achieve smarter water quality management, network improvements, better customer service and more intelligent work processes. Our digitalisation transformation will also benefit our operators by giving them opportunities to train in realistic simulated environments and helping them to become more efficient.

Still, the success of our endeavour will rely on more than just hardware. We will therefore also continue to nurture our human talent, collaborate with others to maintain a thriving water industry, and reach out to members of the public to seek their partnership in water conservation.

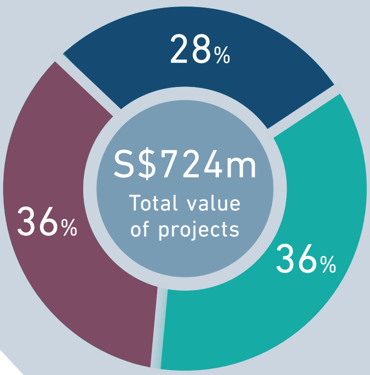
Digitalisation has given us new tools as we head into an increasingly uncertain future, but our goals remain the same. We hope that you will continue to join us as we embark on the next chapter of PUB's journey.

Harry Seah
Deputy Chief Executive (Operations)
PUB, Singapore's National Water Agency

R&D in Numbers

Since 2002, PUB, together with stakeholders dedicated to solving Singapore's water challenges, have collectively committed more than 700 million dollars in water R&D. These range from fundamental, proof-of-concept studies to demonstration-scale trials in operational domains across the water loop. PUB works closely with its collaborators to de-risk and scale up promising technologies. As a result, one in every two projects carried out under PUB's Research & Development Fund progresses to implementation or the next development phase.

R&D INVESTMENT (SINCE 2002)



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

ACROSS THE WATER LOOP

31% WATER TREATMENT, DESALINATION & REUSE

18% WATER QUALITY & SECURITY

16% USED WATER TREATMENT

14% SMART TECHNOLOGIES

8% WATERSHED MANAGEMENT

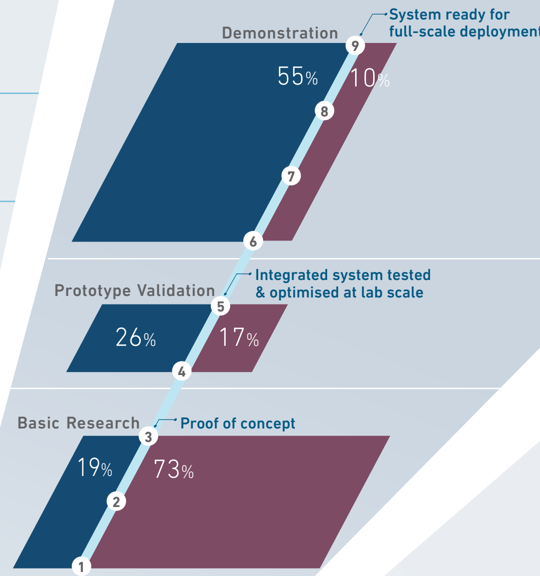
6% NETWORK MANAGEMENT & WATER CONSERVATION

5% INDUSTRIAL WATER SOLUTIONS

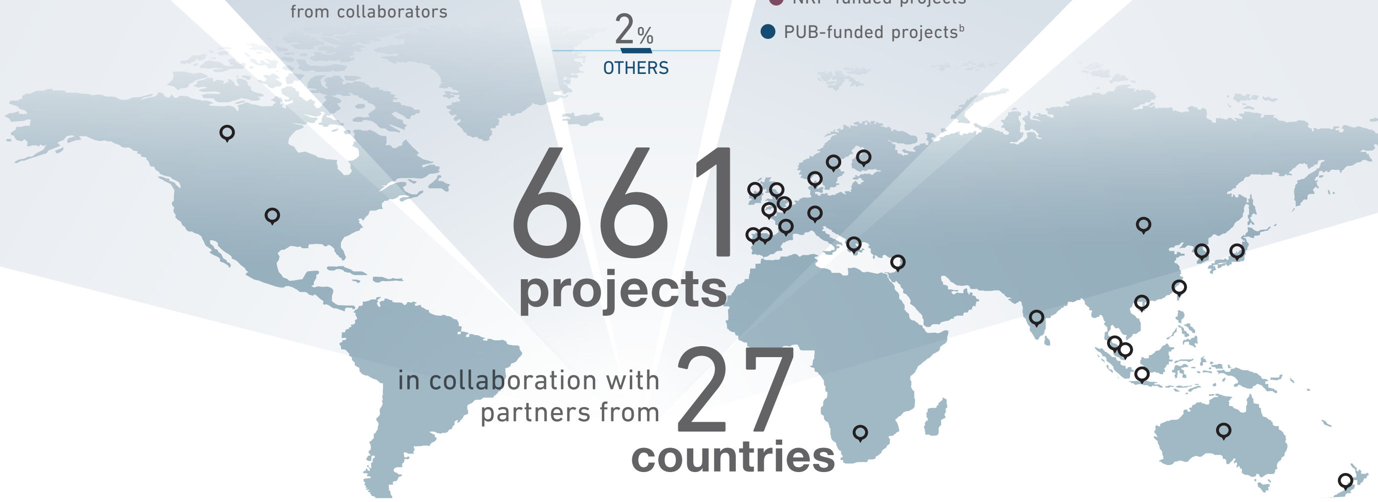
2% OTHERS

ACROSS THE TECHNOLOGY READINESS SPECTRUM

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



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



84% of projects[b] increase in TRL when completed

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

[a] Each TRL corresponds to a specific R&D stage.
[b] Refer to projects that were completed in 2013 or later.
[c] Refer to projects funded under PUB's Research & Development Fund.

Statistics valid as at Dec 2018

Targets & Focus Areas

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

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

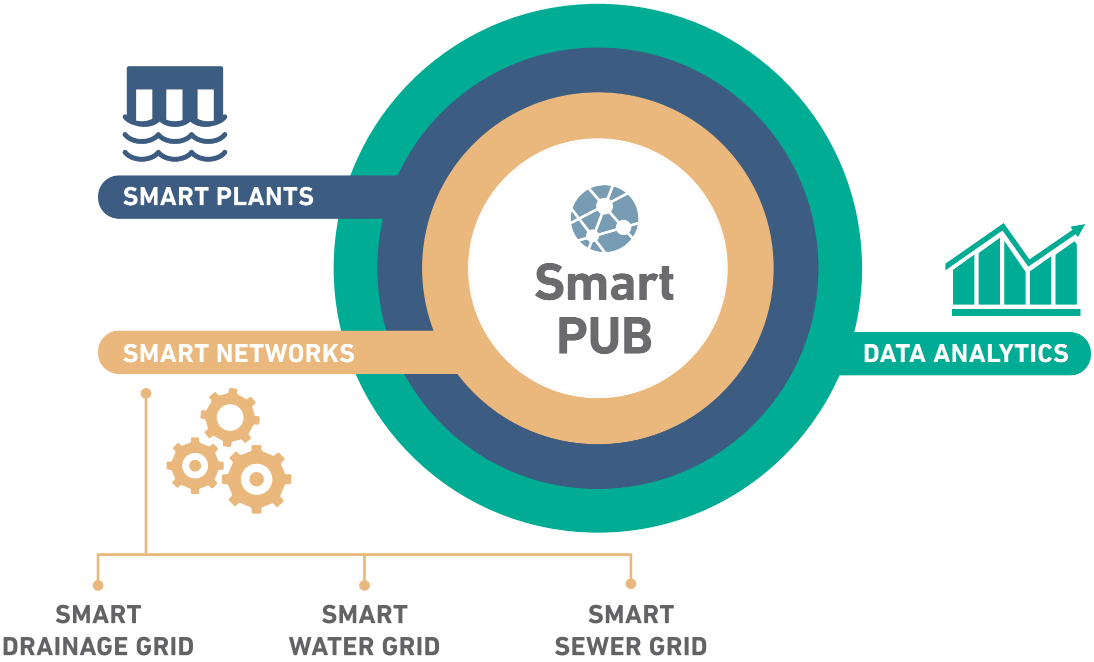
Target
Operational or R&D goals

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

Smart PUB

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



Smart PUB

SMART PLANTS

Operational excellence and productivity

- IoT devices
- Data analytics
- Automation through robotics

Pilot-testing various smart technologies in our installations, including AI systems for data-driven operations, digital twin, predictive maintenance, autonomous systems

Outcome

Operator with

- In-situ equipment data – with sensors for real-time condition sensing
- Smart goggles – to superimpose standard operating procedures in the wearer's view, with his/her hands free
- Smart wearables (e.g. smart watches) – can communicate via wireless network to track the wearer's location, the health condition (heart rate, body temperature...)

Autonomous robots, or drones

- To automate manual labour intensive tasks
- For security surveillance

DATA ANALYTICS

Business intelligence tools for

- Demand projections, leak analysis, studying trends and correlations of pipe failures with pipe material, age, length, and environmental factors
- Analysing capital and operating expenditure
- Detecting anomalies in financial workflows and for procurement analysis

Data Analytics Platform to incorporate data from multiple source systems for automated processing, to

- Reduce the need for manual acquisition and processing to support multi-dimensional analysis for various corporate and operational functions
- Address the current situation of data in silos by integrating more data streams and enhancing data visibility for decision making

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

SMART NETWORKS

Target: To monitor the health and performance of our water, drainage and used water networks with extensive sensors

SMART DRAINAGE GRID

a comprehensive suite of flow and water level sensors and CCTVs have been installed islandwide

R&D area of interest: Data mining and analysis of meteorological and hydrological data to correlate rainfall and hydraulic performance of our drainage systems

Work in progress: To deploy more sensors and CCTVs

SMART WATER GRID

more than 300 sensor stations installed islandwide

R&D area of interest: Monitor water quality, flow and pressure of the potable water network

Work in progress: Additional sensor stations to

- Improve the coverage of real-time monitoring
- Improve accuracy of hydraulic models for pressure management and valve simulations
- Enable operators to pre-empt potential problems in the network

SMART SEWER GRID

a holistic network of level, flow, Micro-Electrochemical Sensors (MES) and Volatile Organic Compound (VOC) sensors islandwide

R&D area of interest:

- To monitor real-time sewer data such as water quality, flow and level
- To predict service disruptions such as sewer chokes, and
- To provide decision support on pre-emptive actions

Work in progress: Developing a sewer analytics management system to provide predictive intelligence and decision support.

To increase the sensor coverage

- For optimising the network maintenance and rehabilitation,
- To pre-empt and detect anomalies within the sewer network

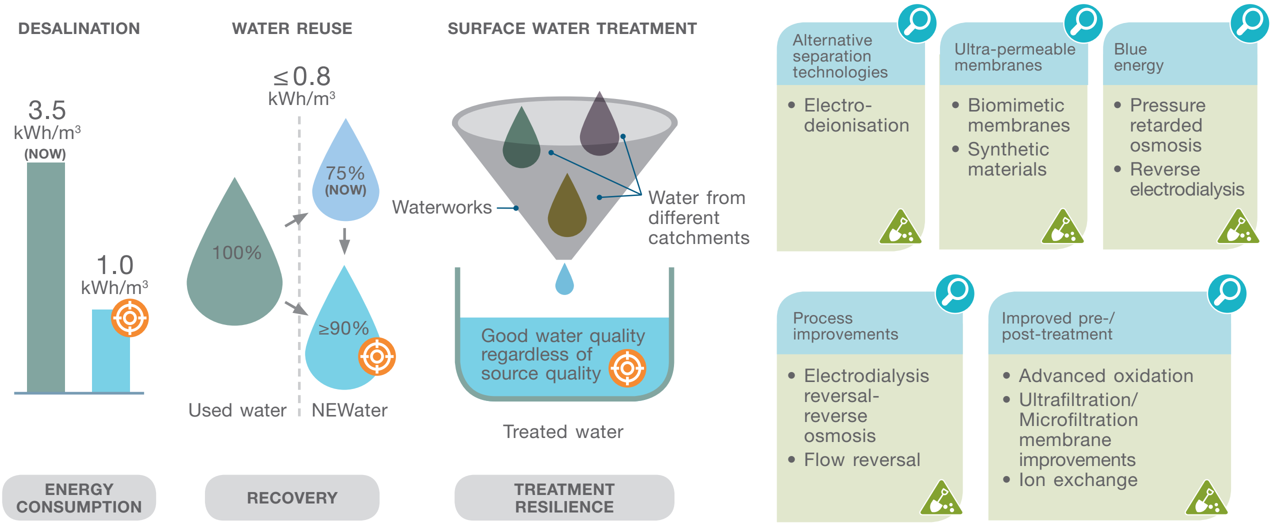
Outcome

Smart Drainage Grid	Smart Water Grid	Smart Sewer Grid
Enhanced system oversight and situational awareness to support waterway operations, fast response and mitigation to manage floods	Early detection of pipe bursts	Reduction in service disruption events and shorten response time for crew dispatch through automated works prioritisation

Water Treatment, Desalination & Reuse

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

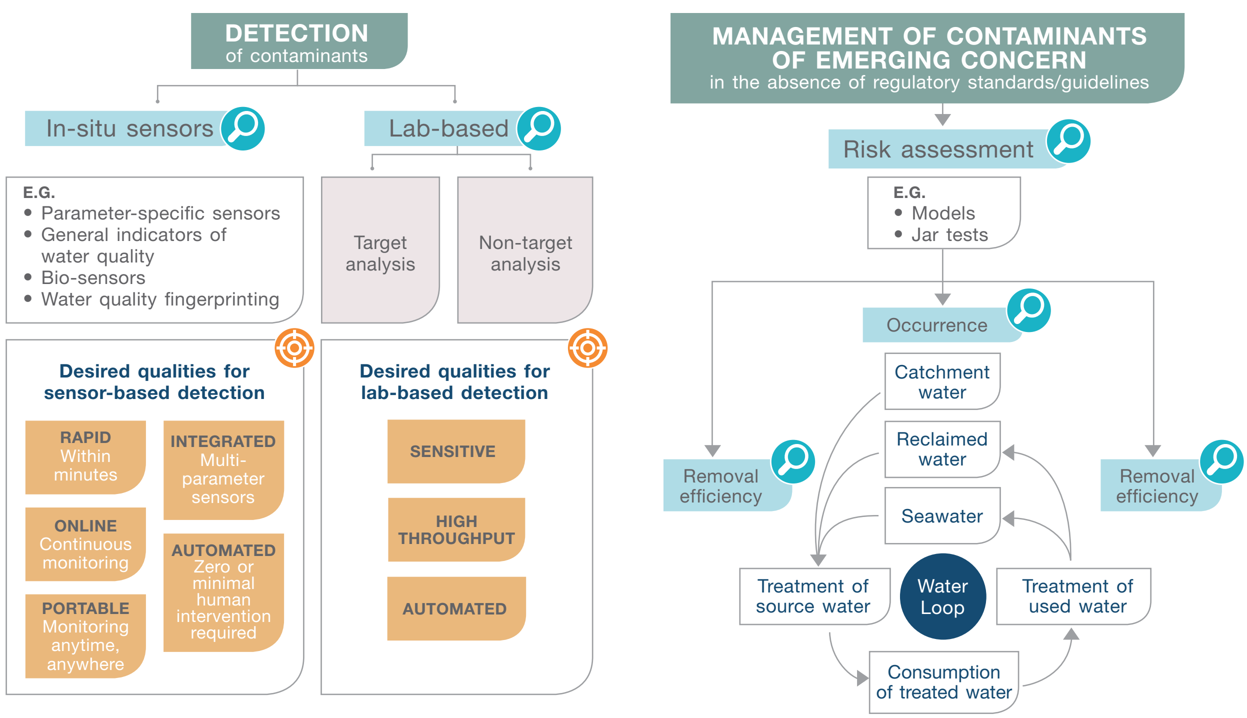
The challenges faced in producing potable water varies with the type of source water. Seawater and used water streams offer a potentially inexhaustible supply of water, but the current desalination energy requirements and NEWater recovery efficiencies pose barriers to their sustainable use. For surface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



Water Quality & Security

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

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



Used Water Treatment

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

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

Energy self-sufficient water reclamation plants

Energy self-sufficiency

CURRENT: 25%*

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

SHORT TO MID-TERM: 75% TO 85%

Biosorption + low-energy membrane bioreactor + sludge preconditioning

Liquid treatment

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

Solids treatment and biogas generation

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

LONG-TERM: 100%

Biosorption/Anaerobic membrane bioreactor + mainstream anammox

Liquid treatment

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

Biogas generation

- Super heated steam turbine

SLUDGE REDUCTION: > 50%

- Thermal hydrolysis process
- Ultrasonic sludge disintegration
- Thickening and dewatering
- Phosphorus recovery

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

Watershed Management

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

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

QUALITY

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

QUANTITY

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

Intelligent watershed management (data mining & analytics)

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

Watershed water quality and aquatic ecology management & modelling

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

Climate change 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

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.

Water Supply Network

PROACTIVE ASSET MANAGEMENT

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

REAL-TIME MONITORING

- To monitor network operation and health in real-time (pressure, water quality, flow, SR level and pump operations)
- To enable more accurate simulations and analysis of planned operations

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

DATA-DRIVEN CUSTOMER ENGAGEMENT

- To enable customers to make informed decisions regarding their water usage by empowering them with data

NOWCAST & FORECAST SEWER WATER LEVELS

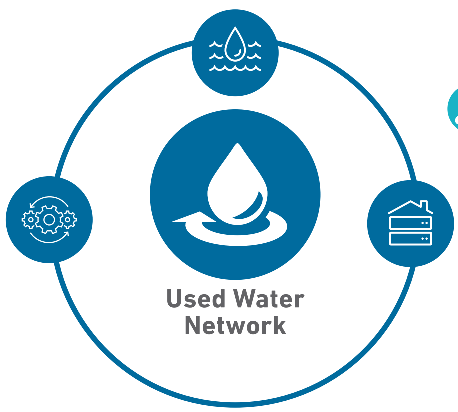
Sewer analytics & modelling system

- 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

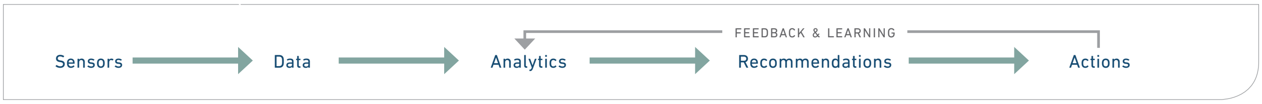


ASCERTAIN RISK & IMPACT OF NEW TRADE PREMISES

Trade effluent module

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

Workflow envisioned for used water management systems



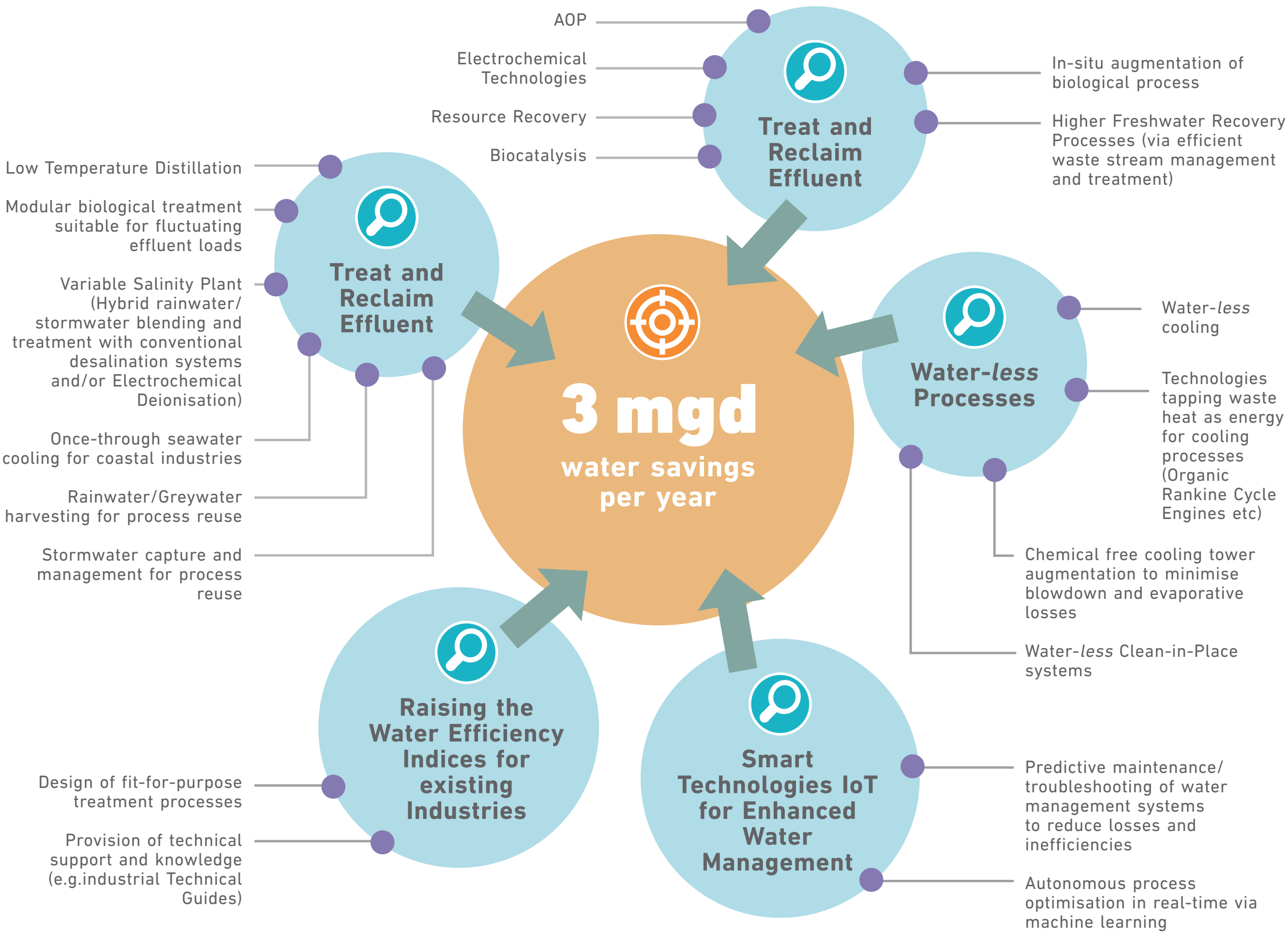
Industrial Water Solutions

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

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

Target Industries

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



Commercially available technologies

Collaborate with Us!

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

FUNDING SUPPORT (PUB)

A

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

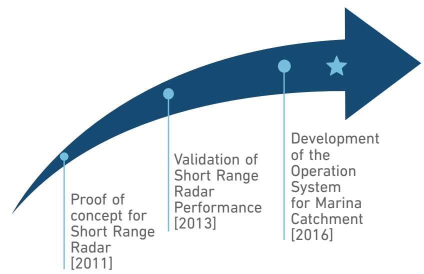
Research & Development (R&D) Fund

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

- **Key criteria:** Applied R&D with potential for implementation
- **Target research area(s):** PUB's R&D **Targets & Focus Areas**
- **Openings:** Ongoing application
- **Application platforms:** Indicate interest to table a proposal at *pub_research@pub.gov.sg*

Featured project: Rainfall Monitoring and Urban Flood Management System for Singapore

In collaboration with DHI and H2i



★ *Scaling-up of the operation system to whole of Singapore is on-going, with the deployment of 3 additional radars*

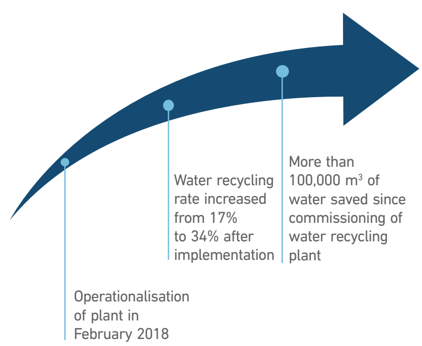
Industrial Water Solutions Demonstration Fund (IWSDF)

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

- **Key criteria:**
  - Water consumption should exceed 10,000 m³/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
- **Target research area(s):** PUB's R&D **Targets & Focus Areas** for Industrial Water Solutions
- **Openings:** Ongoing application
- **Application platforms:** Download Project Assessment Form from *www.pub.gov.sg/research/industrialwatersolutions/funding.* Submit completed form through *pub_one@pub.gov.sg*

Featured project: Dicing and Backgrinding Effluent Treatment Plant

In collaboration with RF360



FUNDING SUPPORT (NRF)

Competitive Research Programme (Water)

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

Project to be carried out in Singapore

Varies across Request-For-Proposals (RFPs); broad aim of helping PUB meet its operational targets

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

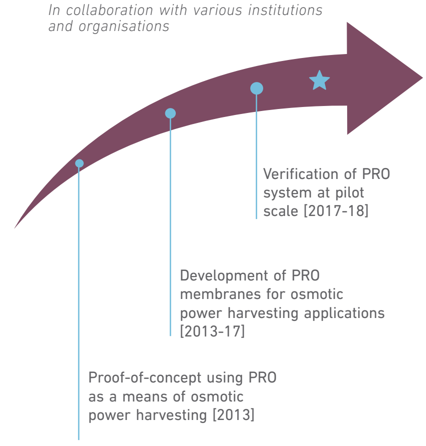
Periodic RFPs, announced through

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

Request to be included in mailing list at
pub_crp_water@pub.gov.sg

Pressure retarded osmosis (PRO)

In collaboration with various institutions and organisations



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

Living Lab (Water)

Incentivise the adoption of new technologies, facilitating commercialisation

Involve a solution provider and an adopter

Carried out in Singapore

Only Singapore-registered businesses and organisations are eligible

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

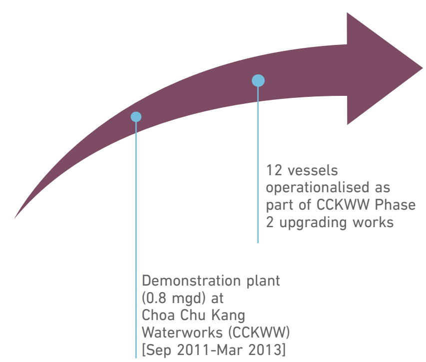
Project shall involve the demonstration of a water technology that is close to operational stage by an adopter.

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



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

TESTBEDDING OPPORTUNITIES

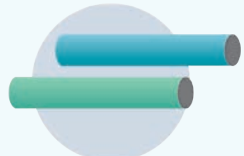
B

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

Operational Installations & Sites


Waterworks


Water Reclamation Plants


Potable & Used Water Networks


NEWater Factories

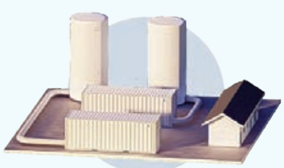

Reservoirs


Variable Salinity Plant


Desalination Plant

- Actual operating environments
- Technical support from ground staff

R&D-dedicated Facilities


Tuas R&D Facility
Desalination technologies


Van Kleef Centre
Freshwater research

- Laboratory amenities* and research/testbed spaces

** Applies to Van Kleef Centre only*

C

TRANSLATION & COMMERCIALISATION

In order to capture the value, ensure continuity and further developments of the R&D projects, PUB, together with industry partners, aims to support the translation and commerclisation of these technologies.

TECHNOLOGY TRANSLATION (INDUSTRY PARTNERS)

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 partners include:

Separation Technologies Applied Research & Translation (START) Centre

The START Centre is set up as a national-level facility to bridge this gap, and to provide significant risk mitigation for the commercialisation of materials, equipment and processes related to separation technologies. The benefits are manifold. START serves as a vital platform for academic and research institutions to transform their innovative technologies into commercial products for key industry players.

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.

COMMERCIALISATION (PUB - SINGAPORE WATER EXCHANGE)

Singapore Water Exchange (SgWX) aims to create a favourable environment to accelerate commercialisation by housing a vibrant ecosystem of water companies across the value chain to leverage mutual strengths to push the frontiers of water innovation and business growth. It is a global hydrohub dedicated to the water industry for like-minded professionals to converge and network to tackle global water challenges. Companies housed in Singapore Water Exchange will also have access to networking activities and a suite of services that support technology development, corporate functions, financing, and entry into key regional markets.

COMMERCIALISATION ECOSYSTEM

- Leverage the ecosystem to gain market access in the region
- Opportunities to showcase your innovation through actitivites that convene water professionals at SgWX
- Network with industry partners and form alliances to strengthen your value propositions
- Access a pool of novel technologies to complement and complete your range of solutions
- Investor network to access funds for your scale-up/ financing
- Mentorship and programmes to accelerate commercialisation
- Provide insights to market challenges and opportunities

GENERAL ENQUIRIES

A B *pub_research@pub.gov.sg*

C *pub_waterhub@pub.gov.sg*

Scan for more information

The smart utility of the future

Artificial intelligence, big data and smart work redesigns are the key to PUB's next leap forward - transformation into a smart utility that empowers the management, employees and members of the public.

From healthcare to transport to retail, digital technologies are transforming the ways that Singaporeans live, work and play. In telecare, clinicians can now keep track of their patients' well-being through wearable technologies, and remotely conduct rehabilitation and therapy sessions for them in the comfort of their homes. Singaporeans can also download mobile apps and use fitness bands to clock their physical activity and monitor their diet.

In transport, artificial intelligence has made it possible to develop new and more efficient ways to travel. On-demand public buses are now being trialled in parts of Singapore, offering commuters faster and more convenient journeys, improving intra-town connectivity and accessibility, particularly for the elderly, families with young children, and the less mobile. Driverless vehicles could also spell an end to manpower shortages in the sector.

Digitalisation is making waves in people's lives, even for municipal services and the retail sector. For example, members of the public can use the government's OneService mobile app to find locations of parking spaces, get dengue clusters alerts, provide feedback and more. In retail, business owners are experimenting with a range of automated and robotic technologies, such as self-checkout counters and robot waiters, to boost their productivity and enhance work processes.

In the midst of this digital transformation, PUB has been making its own forays into technological innovation and integration of our current capabilities and assets with newly emerging digital tools. Two such projects in particular, have helped us to improve our rainfall predictions and stormwater management.

Radar rainfall observation and nowcast

Over the years, Singapore's storms have been increasing in frequency and intensity due to climate change, adding to the risk and occurrence of flash floods across the country. With this trend set to continue in the future, PUB has been looking into more comprehensive and advanced methods to monitor and forecast quantitative rainfall at catchment scale, so as to provide early heavy rainfall warnings for flood prone areas and hotspots as well as rainfall at high resolution to be used in hydraulic models for flood and reservoir operations. This helps PUB to put in place more effective flood prevention and mitigation measures.

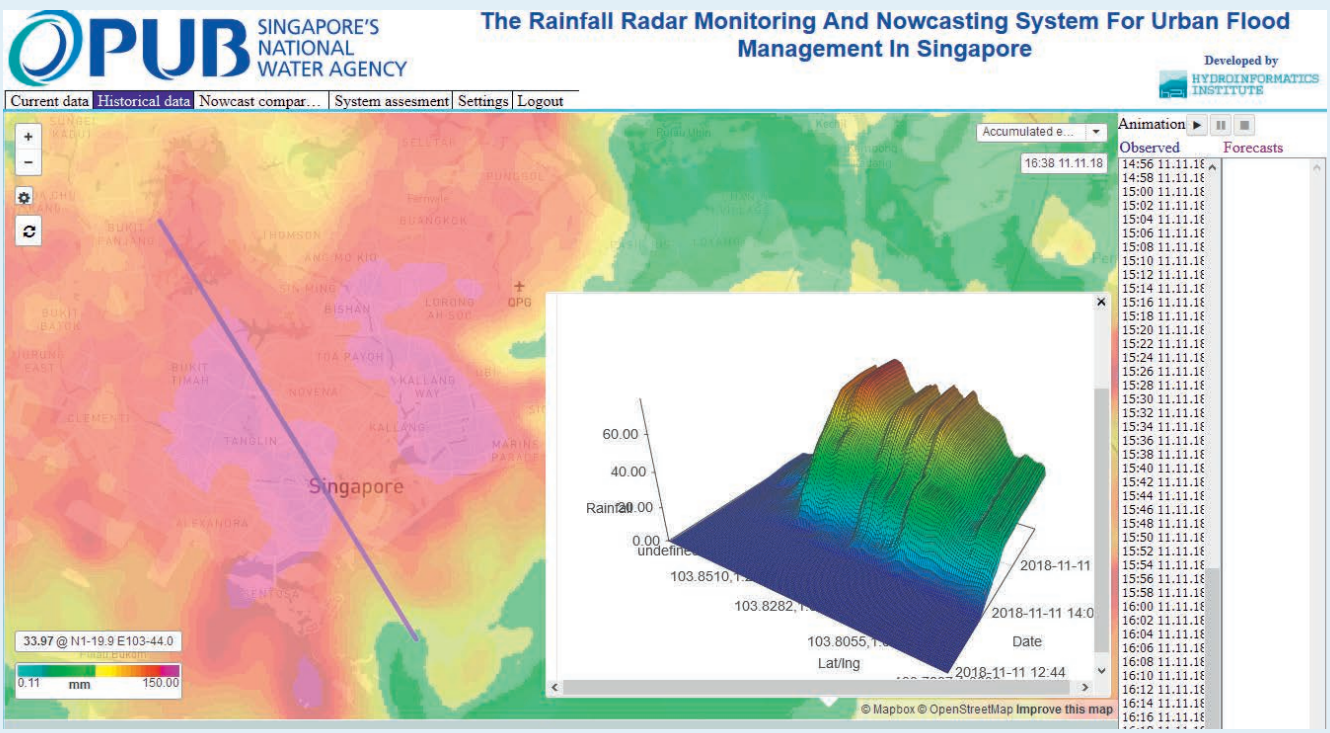
In 2016, PUB started working with the Hydroinformatics Institute and Furuno Singapore to develop a state-of-the-art rainfall monitoring and prediction system that uses X-band dual polarimetric doppler weather radars. Unlike conventionally-used C-band radars, the X-band ones are smaller and can be placed more easily in urban environments, such as rooftops. They are also less expensive and operate via normal power supply.

Three X-band radars have been installed across Singapore in the northern, eastern and western parts of the country respectively. Having three radars compensates for the signal power attenuation that can occur during heavy rainfall and which creates blind spots in the radar readings. It also allows for constant coverage even when individual radars are undergoing maintenance.

The monitoring and prediction system seamlessly merges the radars' observations into a single comprehensive rainfall map. The 100 km by 100 km map covers the whole of Singapore and its surroundings at a spatial resolution of 100 m x 100 m per pixel, and adjusts itself in real-time when any of the radars experiences signal attenuation.

Figure 1: Picture of one radar installed at woodlands booster station

Figure 2: Screenshot of the website created for PUB to see the data from the system



As part of this project, PUB and its partners also developed a nowcast model that has algorithms to determine the movement as well as growth or decay of rainclouds, enabling it to produce rainfall forecasts for the next 90 minutes. The movement algorithm operates on the principle of cell tracking. On the other hand, the growth and decay algorithm works via a linear function that looks at a storm's current growth rate and intensity, and compares the data to that of a large set of historical events.

So far, the nowcast model has achieved a 65 percent probability of detection at 30 minutes' lead time, above PUB's requirement of 55 percent. All of the information produced by the monitoring and prediction system is also available to PUB staff via a web interface that supports them in their live management of predicted heavy rainfall, and in their post-event analysis of heavy storms or even whole seasons, such as the North-East monsoon season. In the event of a heavy rainfall forecast, SMS alerts are also sent to the relevant PUB staff so that they can take timely mitigation actions.

The X-band radar system also plays an integral role in another one of PUB's major digitalisation projects - the Catchment and Waterways Operations System (CWOS). The CWOS project started in mid-2015 as a collaboration between PUB and French utility SUEZ. The system integrates data from several sources including the radar, water level, flow and quality sensors in real-time, thus providing useful and timely information on the current conditions in the Marina reservoir and catchment for PUB's officers to take appropriate actions.

From the beginning, the system was designed and developed with the input of different groups of PUB staff to ensure that it would meet their diverse needs and subsequently improved iteratively according to their feedback. A key objective during its development, for example, was to reduce the latency in its data sources in order to improve the response time of PUB's officers during heavy rainfall events.

The system has the capability to automatically detect anomalies through data analytics, and provides notifications to PUB staff for decision making. The CWOS has successfully integrated hydraulic and hydrological simulation models to anticipate changes in water levels and flows in the Marina catchment's drainage network. Furthermore, an optimisation module has been developed and implemented to advise the Marina Barrage's staff on the number of gates and pumps to be operated at any given time.

Since the CWOS was deployed, it has provided optimised operations strategies to the Barrage's staff with sufficient lead time to take appropriate actions. With its success in the Marina catchment, PUB is looking into expanding its use to other reservoirs.

The grand digital design

Beyond the radar and CWOS systems, PUB is also venturing into the digital age in a myriad of other ways. Last year, we introduced the Smart PUB Roadmap, a vision of how we plan to digitalise Singapore's entire water system to improve our operations and meet the country's future water needs. The roadmap's projects will not only boost our resilience, productivity, safety and security, but also shorten our incident response times.

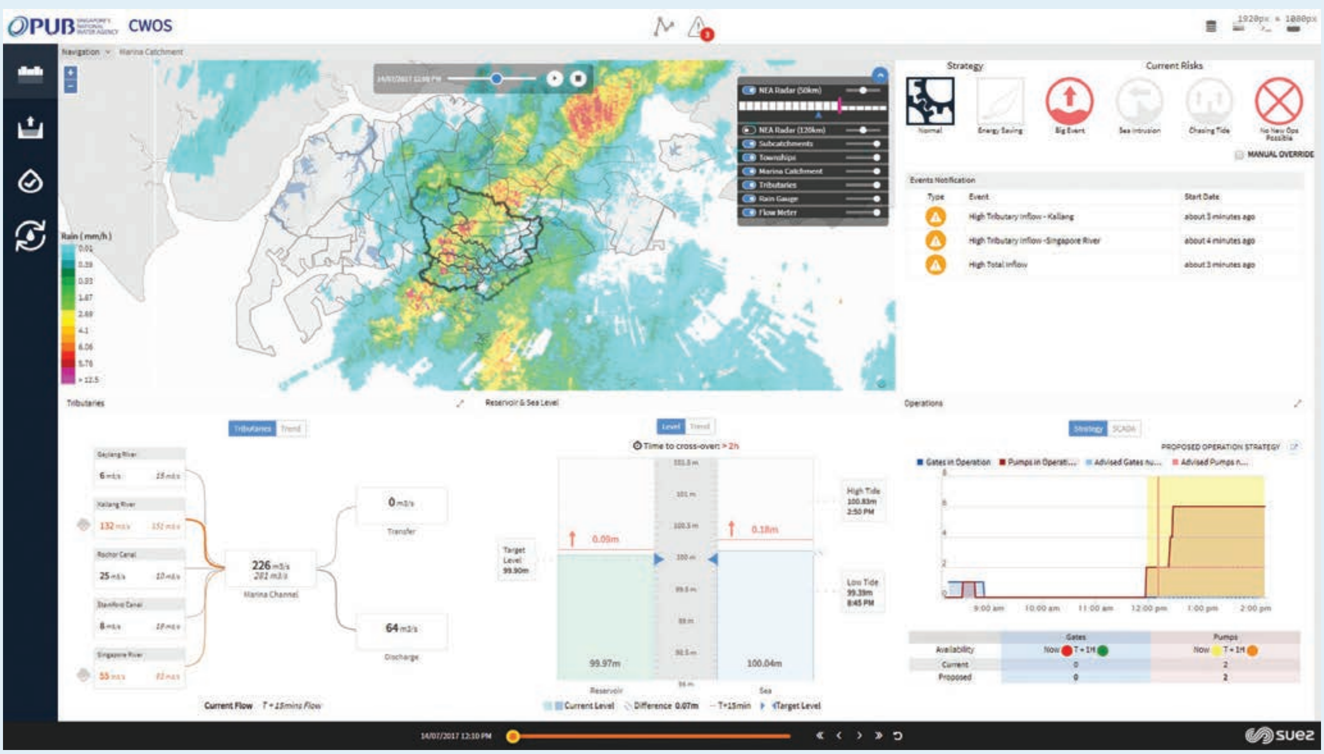


Figure 3: Marina Barrage operations overview – Numbers and values are for illustration purposes only.

The initiatives, for example, include using artificial intelligence and automation to make our water quality management smarter. We have developed a low-cost and portable device called the Remote Micro-Invertebrate Detector that can be used by officers on-site to detect and identify images using artificial intelligence, with split-second imaging to determine the presence of micro-invertebrates in water samples.

The device is linked to a mobile app and chat-bot, which allows the system to test water samples in real-time and around the clock, as well as respond to commands, send live image reports and trigger alerts when anomalies are detected. Since current monitoring methods are labour-intensive, relying on trained biologists to manually identify and enumerate micro-invertebrates under a microscope, this new, fully-automated method will significantly boost PUB's productivity. We intend to equip all relevant officers with this device by the end of 2020.

PUB is also test-bedding an autonomous boat that can brave choppy waters to carry out real-time water quality monitoring via on-board sensors, collect water samples, and take high-resolution photos and videos of actual water conditions. The boat is programmed to avoid obstacles in the water and self-navigate to designated sampling points. It can be used in both reservoirs and the sea.

PUB is also looking into other digitalisation projects to improve our management and maintenance of water and sewerage pipelines. We are creating a pre-emptive leak management system that will use data analytics to identify water pipes at high risk of leaks so that these can be repaired or replaced first. We are also developing similar smart analytics programs and predictive management capabilities to better maintain the sewers in Singapore.

PUB has developed an Automated Laboratory System (ALS) that can test two to three times more samples in the same amount of time and operate non-stop to boot. With the ALS automatically scanning and recording samples' data based on their QR codes, officers no longer need to carry out this time-consuming and laborious task, freeing them up for other work.

PUB has also invented a building information model program to automate checks on building plan submissions. Industry professionals such as architects and building engineers can go to an online portal and use the program to check their designs for compliance before submitting them to PUB formally, eliminating the need for resubmissions and significantly reducing the processing time for their applications.

Even training will benefit from the adoption of digital technologies. Virtual Reality (VR) tools, for example, have taken training for PUB operators to the next level. With the use of a VR headset and a pair of handheld sensors, water reclamation plant operators can now practice starting up and shutting down a dewatering centrifuge, performing critical maintenance checks and responding to operational abnormalities in an immersive and realistic simulated environment.

"The integration of smart technologies in Singapore's water loop opens up new opportunities for us to enhance our system oversight and situation awareness. Data-driven insights will also help us to attain higher levels of operational efficiency, improve our incident response times, and ultimately serve our customers better," said PUB's Chief Information Officer, Michael Toh.

Giving power to the people

With digitalisation, Singaporeans can also look forward to getting more timely information about their water use. Currently, PUB manages about 1.5 million water meters that are read manually every two months for billing to consumers. By using smart water meters, we could reduce the manpower needed for this task and provide households with more up-to-date information about their water consumption.

To collect the water consumption data, smart wireless battery-operated radio devices would be installed on water meters at the consumers' premises. The data would be sent wirelessly to a server daily for analysis, and households would be able to review their past water consumption trends through a mobile app. As monitoring would be conducted around the clock, the detection of continuous water usage throughout a 24-hour period would also trigger an alert to the affected consumer to check for suspected water leaks.

In 2016, PUB, in partnership with SUEZ, tested a smart automated meter reading (AMR) system in about 500 households in Punggol. The results showed that the participating families reduced their water use by about five percent on average through better water conservation habits and the earlier detection of leaks. In fact, one household saved 8,000 litres of water after their app alerted them to a leak in their water closet. PUB is now exploring an island-wide roll-out of the AMR system.

To encourage more people to conserve water by taking shorter showers, PUB is also studying and validating the impact of smart shower devices. These devices are attached to shower fittings and provide users with real-time information about how much water is being used through a display panel or colour codes. Since they are powered by water flow, they do not require batteries or electricity. Users can also set water conservation goals and monitor their usage history through an app.

In 2015, PUB trialled the devices across 500 households and found out that they helped to reduce water use by about five litres per person per day. This could enable households to cut their monthly water usage by about three percent. PUB is now deploying the devices in 10,000 new homes to further evaluate their effect.

"With all of these digital technologies, the holy grail is to reach the point where we are as perfect as we can be," said Mr Harry Seah, PUB's Deputy Chief Executive (Operations). "If we can accomplish that, we will have fewer problems, and we will be able to devote more time and resources to the problems that do occur. Our engagement with the public will be better. In this way, everyone, from PUB to members of the public, will have a wonderful experience when it comes to our water sector."

Water Security: The other side of it

With critical infrastructure such as water treatment plants increasingly making use of digital technologies in their routine operations and to boost efficiency, beefing up cybersecurity hygiene is now a top priority for many nations.

Figure 1: The Secure Water Treatment (SWaT) testbed

In 2017, Britain set out a water sector cybersecurity strategy for the first time, noting that "credible cyber threats... could manifest in a number of ways, including through the disruption of water supply or affecting the quality of the water supply".

Just a year earlier, two incidents in the United States had underlined the potentially fatal consequences of a successful attack. Telecommunications giant Verizon's cybersecurity arm reported that hackers compromised a water treatment plant in the country and altered the amount of treatment chemicals added to the water supply. The plant's managers detected and reversed the changes before customers took ill.

At around the same time, prosecutors in New York charged seven Iranian hackers with gaining digital access to a dam in a suburban county. The prosecutors said that if the dam had not been undergoing maintenance, the hackers would have been able to control a sluice gate used to protect nearby properties from flooding.

In Singapore, iTrust, a centre for cybersecurity research in the Singapore University of Technology and Design, established the Secure Water Treatment (SWaT) and Water Distribution (WADI) testbed facilities in 2015 and 2016 respectively to give researchers a safe and realistic space to conduct experiments and test their cyber defence technologies outside of operational plants. Both testbeds were designed and built in consultation with the PUB to closely mimic the processes commonly used in Singapore's water plants.

A realistic testing environment

The SWaT testbed replicates a six-stage process for treating water. The process includes steps to take in raw water, disinfect and balance the pH value, filter it via an ultrafiltration system, de-chlorinate it using ultraviolet lamps and then feed it to a reverse osmosis system. A backwash stage uses water produced by the reverse osmosis to clean the membranes in the ultrafiltration stage.

The cyber portion of the testbed consists of a layer communications network, programmable logic controllers (PLCs) that receive sensor data and relay commands to a host of actuators, valves, pumps and motors during the water treatment process, human machine interfaces, a supervisory control and data acquisition (SCADA) workstation and a data historian, which records the logs of processes running in the system.

The WADI testbed comprises two elevated reservoir tanks, six consumer tanks, two raw water tanks and a returned tank. It also has chemical dosing systems, booster pumps and valves, instrumentation and analysers. The testbed takes in a portion of SWaT's reverse osmosis permeate, thus forming a complete and realistic water treatment, storage and distribution network across the two systems.

With the two testbeds, researchers all over the world have access to an industrial-grade and one-of-a-kind – in scale, magnitude and interconnectivity – platform to conduct experiments and research to validate their models and theories about cyberattacks, as well as to test the robustness of cyber protection methods that are developed. The testbeds can also be used to train water utility operators and engineers to manage cyber incidents.

In fact, the interconnectivity of the two testbeds at iTrust would allow researchers to witness the cascading effects of cyberattacks on one testbed to another. It also installed a different brand of PLC in the WADI testbed compared to the one in SWaT so that researchers can test their cybersecurity defence models on multiple brands to assess their robustness and implementation flexibility.

After three years of intense research, five patents have been filed for innovative technologies aimed at detecting cyberattacks from multiple angles and enabling systems to recover from them quickly. While they were developed independently, efforts are being made to integrate them into a suite for cyber-physical system owners and operators, and cyber security solutions providers. Here's a look at the technologies:

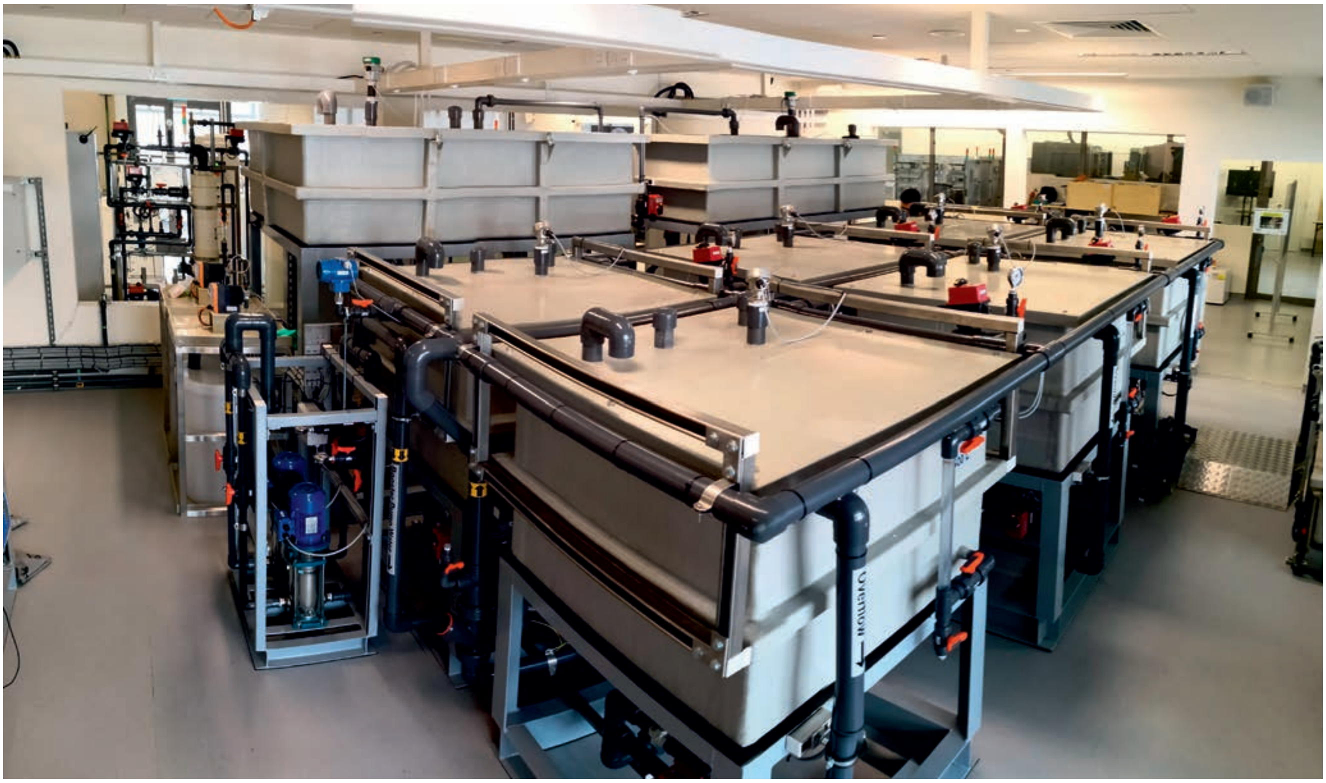


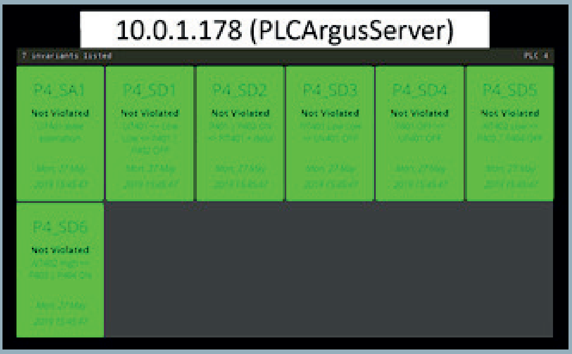
Figure 2: The Water Distribution (WADI) testbed

Argus

The Argus attack detection and defence technique relies on devices called Intelligent Checkers (ICs) to boost the cybersecurity of a cyber-physical system. "Local" ICs are embedded systems hardware devices that monitor electrical signals and transmit information about the system's sensors and actuators to a "Global" IC that ensures that the system's dynamics have not deviated from the expected performance.

The global IC does so by having access to each of the plant network's stages as well as the process layers – electrical communication (4-20mA protocol), remote I/O (EN/IP), PLCs (CIP), SCADA and historian. A third element, called an independent global IC, acts as a safeguard in case the other checkers are compromised and brings the plant to a safe state or shutdown state if an adverse attack is detected.

Argus provides a layered defence system that detects cyber attackers that have gained unauthorised access to the system. It can distinguish between faults and attacks, and works even in the case of power failure and network failure, such as during denial-of-service attacks. If it finds a deviation in the system's dynamics, it pinpoints the source of the attack on the system and alerts the relevant stakeholders.



Real time monitoring of cyber-physical health of each component of a particle stage. Image shown is the panel for monitoring of Stage 4 of SWaT (i.e. de-chlorination process).

Invariants Violation

One of the ways to detect cyberattacks is to look for anomalies in the cyber-physical system's processes. This means, however, that cyber protection programs have to be aware of the system's normal state, and the rules governing its processes' behaviour. Such rules, which are called invariants, can be identified in two ways.

The design-centric (DeC) approach involves feeding the system's design and its components' specifications into an invariant generator. For a water treatment plant, this could include the plant's process and instrumentation diagram. The data-centric (DaC) approach, on the other hand, creates invariants by analysing data produced by the system's operations.

By studying and comparing the two approaches, an iTrust team found that they work best when combined. DeC can uncover relationships among a cyber-physical system's components and generate invariants beyond the reach of DaC algorithms. DaC programs, for their part, can be used to monitor the system continuously and update design-derived invariants when these become inaccurate due to the system ageing and components becoming degraded.

Water Defence

This method is used to protect water treatment plants from cyberattacks. After conducting a comprehensive assessment of the cyber-physical system, it creates and programs state-dependent and state-agnostic invariants. A "checker code" is then added to the control code in each PLC and executed regularly.

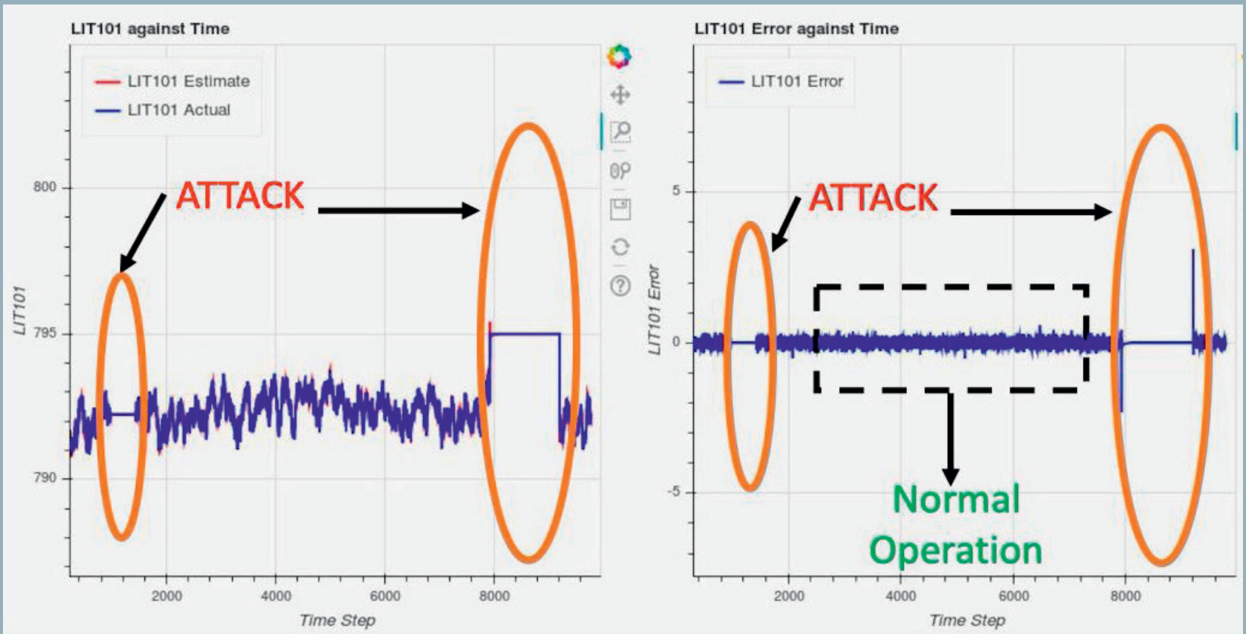
Each time the code is executed, data from system's devices is obtained, control actions computed and applied when necessary, and the invariants checked against the state and other variables, to detect potentially damaging anomalies.

Monitoring screen for Water Defence. Red flashing box indicates detection of a process anomaly (e.g. P1_SA1 at the top left hand corner) while green box indicates that the invariant is not violated.

NoisePrint

NoisePrint detects data integrity attacks on sensors. It creates unique "noise fingerprints" for each part of a cyber-physical system by analysing the noises produced by sensors and processes in that part during normal operations. Since sensor spoofing attacks would cause the noise pattern to deviate from the fingerprinted one, they would be detected and flagged by the NoisePrint technology.

Research has shown that a multitude of sensors can be uniquely identified with more than 90 percent accuracy based on their noise fingerprint, making this technique highly effective.

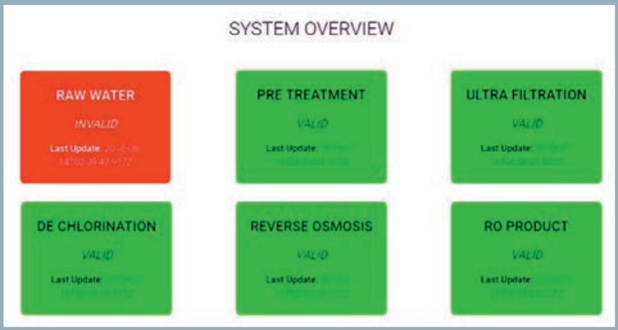


Left hand figure shows the plot of sensor measurements of a water level sensor and the right hand figure (NoisePrint) shows the plot of residual signal of the same water level sensor. Two stealthy attacks were launched at around 1000 seconds and 8000 seconds.

Attack was not picked up by the left hand figure but the change in noise profile was picked up by right hand figure (NoisePrint) as the attacker could not replicate the noise profile during normal operation.

ICS:BlockOpS

This technology uses blockchain to improve the security of data in a cyber-physical system's data historian. It enables data immutability and redundancy, detects attempts to alter or delete the data and alerts plant operators, and allows for quick recovery if the data is actually manipulated.



User interface for monitoring of manipulation to historian data. Affected node turns red upon detection and operator can view registers for investigation as well as to recover data.

EMBRACING DIGITAL TRANSFORMATION

Last year, PUB unveiled the Smart PUB Roadmap, its blueprint to digitalise Singapore's entire water system to improve operational excellence and meet future water needs. In this issue, Mr Harry Seah, PUB's Deputy Chief Executive (Operations), shares his visions for PUB's digital future and how this will revolutionise the way we work for the better. Formerly PUB's Chief Engineering & Technology Officer, and Assistant Chief Executive, Harry oversaw the agency's R&D projects to achieve its goal of a smart water management system.

PUB has been at the forefront of water technology innovation for many years, and its digital roadmap is the next stage of its evolution. What was the vision behind it?

Singapore is at a critical stage. In the coming years, our country's low fertility rate translates into a smaller working population, which may mean that we may have difficulty filling a number of jobs. We have to prepare ourselves and make changes to our operations to do more with potentially less manpower. Digitalising our water system enables us to do that. With sensors, predictive models, automation and other digital technologies, we can solve problems before they occur, minimise inconvenience to people during incidents, and collect data for post-event analysis to create innovative proactive solutions instead of conventional reactive methods. We can also tap on advancements in digital technologies to empower our employees, to help them become more productive, do higher-value work, finish their tasks more quickly towards better work-life balance.

If we look at other countries with low fertility rates, like Japan, they are doing the exact same thing: investing in digital technologies for their water sector. From the engineering point of view, employee point of view, and even the public point of view, digitalisation offers promising opportunities to tackle many future problems.

When some people hear the word "digitalisation", they think of automations and job layoffs. You're saying that's not the case. Can you give us an example of how digitalisation can assist PUB employees to do their work more efficiently?

Let's say you're a plant operator. Now, you have to walk around the plant every day to check all of the equipment. In the digital future, we will have sensors in all critical equipment, so that they can be tracked in the control room. You will still need to do your rounds, but now you can do that with a reduced frequency. If a sensor prompts you that something is wrong with a piece of equipment, when you go to examine it, you'll have a tablet that will give you all the information you need at your fingertips, from when the equipment was installed, to its last servicing date, and which company supplied it.

If you decide that the equipment needs to be shut down for repairs, you can just press buttons on your tablet to isolate the equipment. It can also provide you with real-time updates on the equipment's status and enable you to communicate with the control room remotely. In fact, if you need to alter the plant's operations temporarily, you don't even have to worry about pressing the wrong button because there will be built-in safeguards that prevent errors.

After you have initiated the fault report on your tablet, it will also route the report to the relevant contractor and track the progress of the repair to completion. It will also send reminders to both the contractor and you, including a reminder on the day of the scheduled repair.

If your job involves catchment surveillance, digitalisation will help too. Even if you're extremely hardworking, there are still physical limits to what you can do by yourself. A company might dump its waste into the drainage system right after you leave the site. With sensors, however, you could be elsewhere at the time of the incident, but there would be readings and measurement reports to aid in enforcement and prosecution cases.

That's the beauty of digitalisation. It's as though we are creating many virtual assistants for each of our employees. With an electronic record of a plant's operations, operators won't even have to spend time at the end of their shifts doing handovers. They will be able to do more during their day and still leave work on time. If you take the longer-term view, we may even be able to pass on some of our cost savings from digitalisation to our employees, because they will have more responsibilities.

What are some of PUB's ongoing or upcoming digitalisation projects that excite you personally?

I think the whole of PUB is extremely excited about our plans for Automated Meter Reading (AMR). AMR will help us in the early detection of leaks and reduce water wastage. More importantly, it provides members of the public more information about their water usage, which is key to changing wasteful behaviour. We've done two trials of AMRs in Punggol and Yuhua, where an average of 5% in water savings was observed in the participating households.

In terms of data analytics, AMR presents multiple potential benefits. Singapore's population is ageing, and there are many elderly people who are living on their own. Even the most dedicated social worker will not be able to keep track of his or her charges all of the time. With AMRs, we could "look in" on this vulnerable group, and set alerts in case of abnormal water use. Some examples of red flags could include abnormal water use, such as the constant consumption of water until the wee hours of the morning, or if there has been no consumption of water at all for the day.

Even in terms of enforcement against illegal activities, AMR could hold tremendous potential in its applications. For example, if a company that operates during the day suddenly starts to consume water at night, or if a timber yard suddenly uses a lot more water than usual, the AMR data patterns may trigger an alert for the relevant agencies to investigate. We can work with other government agencies to explore the potential applications. There is a lot that we could do with the technology.

How does the Smart PUB Roadmap build on what PUB has been doing for many years?

We've been digitalising our operations for years, just not in a big way due to the technologies that were available in the market. We started our Water Wireless Sentinel (WaterWiSE) system more than 10 years ago, in 2008. We've been improving it steadily, upgrading it with technologies like acoustic sensors as they become more mature and reliable, so that the results get better and better. We have also put radio-frequency identification tags in our storerooms.

The Smart PUB Roadmap outlines our overarching vision and plans going forward, but it definitely builds on what came before it. PUB is always on a journey towards the optimum: how we can solve our emerging manpower issues, make life easier for our employees, improve our service to the public. Hopefully, you'll see a very different PUB in five years' time.

What advice would you give to current and future PUB employees to prepare them to ride the digital wave?

I think younger Singaporeans will not have any problems embracing digitalisation. It's more about how we can make use of their skills to build the system that we need. If you look at our education system, imparting computing and coding skills is already a big priority. For our older employees, we may need to train or retrain them, and help them to see the benefits of digitalisation. I have to say, though, that engineers are very versatile, and the fundamentals of running and optimising our water network and processes have not changed. Engineering knowledge is still the key, and all these digitalisation efforts add newer and better tools. You can teach people to use tools.

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.

Simulation of water quantity and quality for Marina and Kranji Reservoirs

Using cloud-enabled, real-time models for forecasting

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Predicting reservoirs' water quantity and quality is challenging due to the dynamic and complex processes/links between catchment and reservoir systems as well as uncertainty in forecasting rainfall patterns, and it will only become more difficult in the future due to climate uncertainties.

To overcome these problems, researchers in Nanyang Technological University (NTU) are aiming to show that coupled mathematical models which take into account such uncertainties can better simulate the factors and processes affecting reservoir hydrodynamics and water quality, and thus produce more accurate predictions.

A catchment model, for example, could translate rainfall data into runoff data, which is subsequently used as an input for a reservoir model, so that the latter can better predict how reservoir hydrodynamics and water quality will change (Figure 1). Such enhanced predictions would enable water utilities such as PUB to make even better water management decisions.

As part of the project, the researchers are also refining the understanding of the various system uncertainties so that the entire system can be modelled with greater accuracy.

The researchers have already tapped on the National Environment Agency's rain gauge network, as well other gauges installed specifically for this project, to record rainfall data at five-minute intervals. They have found that there is considerable spatial variability in the rainfall within the Marina Catchment (Figure 2).

They have also shown that tall buildings and structures near reservoirs can exert considerable wind shielding, causing the non-uniform distribution of wind fields over the reservoir surface. This can in turn affect Marina Reservoir flow and water quality behaviour (Figure 3).

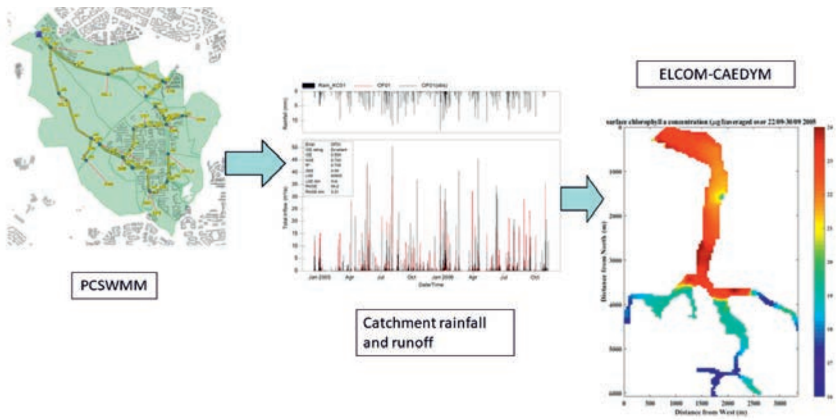

Figure 1: Representation of how a catchment model (PCSWMM) translates rainfall data into runoff input for a reservoir model (ELCOM-CAEDYM), to predict Kranji Reservoir water quality.

As many environmental factors and processes are represented in the mathematical models, running the coupled models could lead to substantial computational stress. To overcome this, the researchers have plans to carry out the modelling on a cluster of computers or in the cloud to minimise run time and maximise its usefulness for decision making.

"By taking advantage of such cloud or cluster computing, we can significantly reduce the coupled model computational time so that predictions of runoff and water quality can be made in, essentially, real-time in future," said Associate Professor Kim Irvine from the National Institute of Education, NTU.

He concluded, "As Singapore continues on its Smart Nation journey and increasingly implements digital technology to further improve liveability and sustainability, it is essential to explore how such technologies can be deployed in the water sector. Using a cluster of computers to speed up computational time is one example."

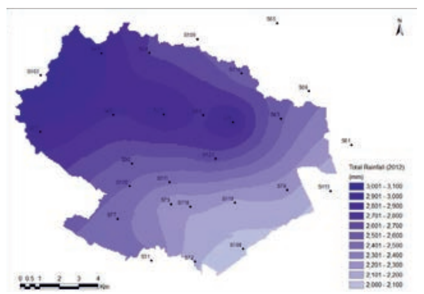

Figure 2: Spatial pattern of annual rainfall in the Marina Catchment for the year 2012, based on the National Environment Agency's rain gauge network.

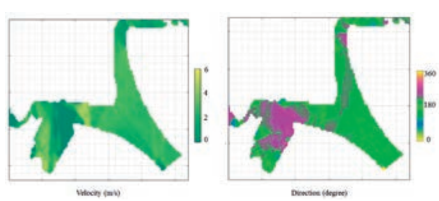

Figure 3: Wind velocity and direction at noon for the South West Monsoon season on 1 August 2014, generated using a combined three-dimensional computational fluid dynamics and probability model with 20 m x 20 m grid cells over the Marina Reservoir. Wind directions are generally from 180-degree with the exception of Marina Bay, where wind direction is shifted to 270-degree due to structures close to the reservoir. Wind velocity is also altered in the Marina Basin, where winds in excess of 5 m/s are observed around the edges of the Marina Bay Sands while velocities are substantially reduced in the wake region.

Creating an Internet-of-Things for water monitoring through new smart water and adaptive technologies

Developing robotic intelligence and cost-effective sensors for big data collection on water quality

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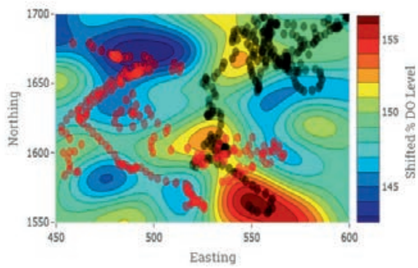
Water utilities need a good understanding of the environmental processes in freshwater bodies, such as reservoirs, in order to manage them efficiently. However, a common problem in environmental monitoring is that water bodies change over time, sometimes quickly, limiting the size of the area that can be surveyed accurately before the field changes significantly. These monitoring efforts are also labour and resource intensive.

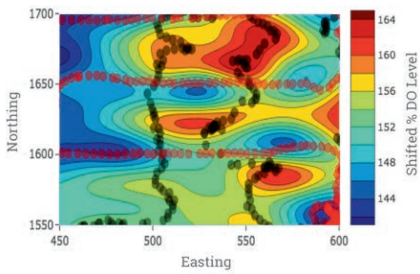
Hence, PUB collaborated with the National University of Singapore's (NUS) Environmental Research Institute (NERI) and Tropical Marine Science Institute (TMSI) in 2014 to fund the development of NUSwan (New Smart Water Assessment Network) - a fleet of cost-efficient and highly versatile robots that continuously monitor the water in our reservoirs. (Figure 1).

Figure 1. NUSwans in Pandan Reservoir, Singapore. Photo Credits: Jack Board, Channel News Asia.

Moving forward, NUS is now developing adaptive sampling algorithms that will improve accuracy of the spatial estimates using minimal survey time. It is also embarking on a joint project with commercial partners to put together a cost-effective sensor package that will make it economically viable to deploy a large number of nodes to collect big data on water quality.



a) Predicted field from data collected along the path planned adaptively. Time taken 1200s, Root Mean Square Error=3.9.



b) Predicted field from data collected along the standard lawnmower path. Time taken 1256s, Root Mean Square Error=6.6.

Figure 2: Comparisons on the performance of spatial estimations using data from the lawnmower and adaptive sampling path show the improved performance from the adaptive path. The RMSE is calculated using the independent data collected on the robots' return paths and its spatial estimates, assuming the field does not change during the period.

As planning the deployment of both mobile and static sensors to collect data efficiently and comprehensively is no trivial matter, NUS is working with Subnero Pte Ltd to create a web-based decision support system that will enable the scaleable collection, management and visualisation of data from the sensors.

NUS is testing Sparse Gaussian Processes (SGP) for field estimation and path planning to coordinate the NUSwan robots. With the adaptive sampling algorithms, the fleet will become smarter in planning sampling routes and collect more useful data. In preliminary field tests, the new algorithms provided reasonable improvements against standard lawnmower missions (Figure 2). The ongoing project will continue to improve and validate the algorithms' performance.

Furthermore, since each NUSwan robot can carry only one water sample, NUS is developing another algorithm with PUB's support, called Sampling and Adaptive Monitoring (SAM), which uses SGP to estimate the field and decision-making frameworks to determine the best sampling location.

The ongoing project will also extend NUSwan's existing web-based interactive mission control capability to include a scalable framework to support new robotic behaviours as well as interfaces for external data analytic modules and environmental models. This addition will allow for more integrated operation of PUB's assets to facilitate better decision-making.

If successful, the research partnership between NUS, PUB and Subnero will improve the accuracy and efficiency of spatiotemporal monitoring. It would also make it economically feasible to deploy a large number of water quality sensors, enhance the NUSwan's operational simplicity and improve the robots' sensing intelligence.

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

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.

Automated identification and counting of algae in Singapore's reservoirs and coastal waters

A pilot project to evaluate an automated imaging flow cytometry system to monitor harmful algal blooms

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Harmful Algal Blooms (HABs) pose a significant threat to the sustainability of Singapore's drinking water supply as they produce compounds that can disrupt the operation of water treatment plants and impact water quality.

PUB carries out routine sampling and monitoring on HABs at our reservoirs and coastal waters. Currently, manual microscopy is used to test for HABs in the waters. However, this method is manpower intensive and has a long laboratory turnaround time.

The rising occurrence of HABs in Singapore has resulted in a need to increase the number and frequency of water samples taken to ensure the quality of our water supply. PUB has embarked on a project that uses new automated imaging and species identification techniques based on imaging flow cytometry (IFC). IFC combines the high throughput of conventional flow cytometry with the sensitivity of microscopy to provide a detailed and comprehensive analysis of individual particles in the water.

One such system, called the Imaging FlowCytoBot (IFCB), is now installed in one of PUB's laboratories (Figure 1), and is examining water samples daily. Algal cells in a flow stream are exposed to a laser, which induces fluorescence and side scatter to reveal useful information that can be used to identify and count each cell.

Since the IFCB can take up to 800,000 photographs of chlorophyll-containing algal cells per day (far too many for human staff to process), machine-learning approaches are being used to automate the taxonomic classification and enumeration of individual algal cells.

The Woods Hole Oceanographic Institution (WHOI) in the United States, PUB's partner for the project, is currently developing species classifiers for the harmful algal species found in freshwater and marine samples from Singapore's reservoirs and coastal waters. When this project is completed, PUB staff will be equipped with the necessary knowledge to create classifiers for other algal species in the future. An example of IFCB algal images from a Marina Reservoir sample is shown in Figure 2.

"The IFCB can provide significant improvements over conventional microscopy through the examination of larger volume samples processed at high speed, with reduced reliance on technical staff's subjective visual inspection skills," said WHOI's Dr Michael Brosnahan, an investigator on the project.

PUB is also exploring other operational uses for the IFCB, such as automated notification to staff when HAB species exceed danger thresholds. After this project is concluded, the next step will be to consider the deployment of multiple IFCBs within Singapore's reservoirs or near its desalination plant intakes to provide autonomous real-time data. Such a network of IFCBs has already been successfully implemented and proven its usefulness in the Gulf of Mexico and other areas of the United States.

Figure 1: The Imaging FlowCytoBot (IFCB) in operation in a PUB laboratory.

"Efficient, automated recognition of target species, with alert systems activated when cell numbers reach a threshold, are critical requirements for HAB monitoring and management," said WHOI's Dr Donald Anderson, principal investigator of the project. "This can be a reality in Singapore in the near future."

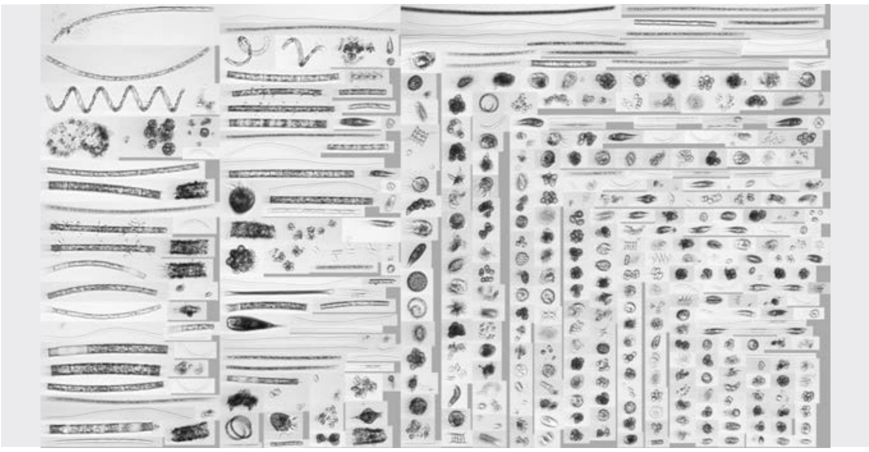

Figure 2: Dashboard showing IFCB images of phytoplankton (single-celled algae) from a sample collected from Marina Reservoir. Considerable diversity is evident, from long chains or colonies of cells to solitary cells. These images were collected just a few minutes after the sample was put in the IFCB.

Tapping on advanced analytics and artificial intelligence for optimising operations and maintenance

Integrating information from different data sources and systems to mine useful patterns and boost fault detection, diagnosis and automation in water treatment plants

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Singapore's demand for water is rising and projected to almost double by 2060. Despite our need for more workers with relevant skills in the water industry, it is likely that we will soon face a shortage of manpower due to declining fertility rate and career aspirations that are at odds with factory work.

To address this problem, researchers from Yokogawa Engineering Asia Pte Ltd are tapping on technological advances in data analytics and artificial intelligence (AI) to develop solutions to optimise industrial processes within the water industry.

Working with PUB, they have embarked on two innovative projects in March 2019 – to enable the early fault detection and diagnoses of equipment, and to augment various operations, respectively. This will allow for proactive maintenance of equipment and facilitate improved operations of the plant, among other benefits (Figure 1). The projects are slated to be completed by February 2022.

Project 1: Early detection of equipment failures

The first project aims to proactively prevent non-performance of plant equipment by diagnosing the possibility of failure at an early stage. Equipment failures can result in plant shutdowns that severely impact the reliability of a plant. Researchers have observed that plant equipment usually show early signs of failure, called failure signatures, well before they malfunction. By focusing on these failure signatures and the information contained within them, plant operators can take timely action and avoid unplanned plant shutdowns.

Project 2: Optimisation of operational processes

In the second project, researchers have proposed the use of data mining techniques and AI-based technologies to improve the operational processes within treatment plants.

Plant operators are often flooded with a large number of notifications or alerts. These notifications or alerts may be unnecessary, false or redundant messages that do not indicate an abnormal situation and more importantly, do not require any action taken by the operator. The high volume of such notifications may overwhelm operators and cause them to miss real alerts that do require prompt actions to be taken. The project will tackle this problem by using machine learning techniques to extract useful insights from notification patterns and other useful informational sources.

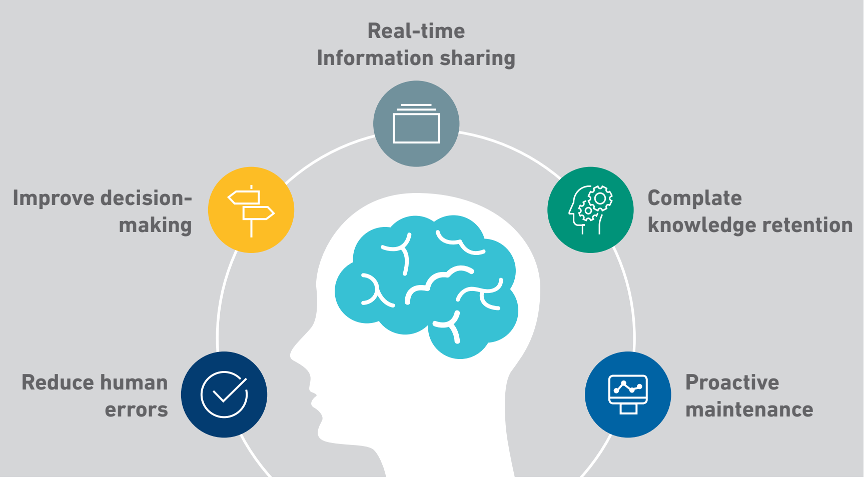

Figure 1: Key focus areas of the projects.

Figure 2: Working hand in hand with digital technologies to boost safety, productivity and efficiency.

The researchers will also look for ways to streamline PUB's safety, efficiency and productivity through the use of digital technologies like data fusion, pattern discovery and artificial intelligence via the insights gleaned and tools developed from this project (Figure 2).

Yokogawa Engineering Asia's Head of Industrial Solutions Research, Co-Innovation Centre, Mr Gokula Krishnan Sivaprakasam said: "We aim to improve PUB's overall knowledge management process through smart technologies like advanced analytics and AI solutions, thereby improving its productivity and operational efficiency."

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

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.

Testing solutions in a Smart Integrated Validation Plant

Using an advanced plant to test and validate new and innovative technologies

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As the world marches towards Industry 4.0, where digital technologies such as automation and artificial intelligence programs change the way goods are produced, more organisations are using testbeds to trial, refine and validate ideas, products and theories before implementing them.

In February 2017, an Integrated Validation Plant (IVP) was constructed to help PUB assess the feasibility of deploying new and innovative technologies in water reclamation plants such as the Tuas Water Reclamation Plant, and other PUB facilities.

For this project, PUB collaborated with Nextan Pte Ltd (the lead in a consortium with prestigious parties such as ABB, Emerson, Hach, and Royal HaskoningDHV) to develop, deploy and integrate various advanced solutions for testing at IVP. Some examples include asset tracking, smart cameras for water purity, environmental Internet-of-Things (IoT) sensors, artificial intelligence analytics, robotics and smart glasses.

One of the key IoT devices being tested at IVP is the Nextan Smart Tracker (Figure 1). As part of PUB's efforts to improve health and safety standards within the plant, staff are equipped with the Nextan Smart Tracker, which has smart sensors that allow for indoor and outdoor location monitoring, vital sign detection and activity classification. The tracker is able to alert the command centre if there is any anomaly in staff's heart rate, so that support and assistance can be rendered quickly.

In addition, one of the key objectives of the collaboration is to move PUB closer to Industry 4.0. We envision the development of smart plants that run on a fully integrated system where all devices and machinery are centrally managed, and information from all end nodes and devices within the plant are processed and translated into meaningful information for better decision-making.

To this end, IVP employs the use of Nextan's OWARE platform (Figure 2), which is able to obtain data directly from IoT devices, including Modbus and Supervisory Control and Data Acquisition (SCADA) systems. This facilitates integration and greatly reduces the time taken to communicate between multiple devices.

Once data is funnelled into the integrated OWARE platform, it can automate plant's processes in real-time, use artificial intelligence to alert operators to potential process abnormalities, help in offline process simulations and analytics for decision support, provide predictions of effluent parameters up to 72 hours in advance, and more.

"This will allow PUB to minimise human error and redirect resources into higher value-added areas," said Nextan's Mr Wilfred Tan, enabling the agency to further enhance its operations and continue to lead in the digital age.

Figure 1: Prototype mock-up of the dongle size tracker

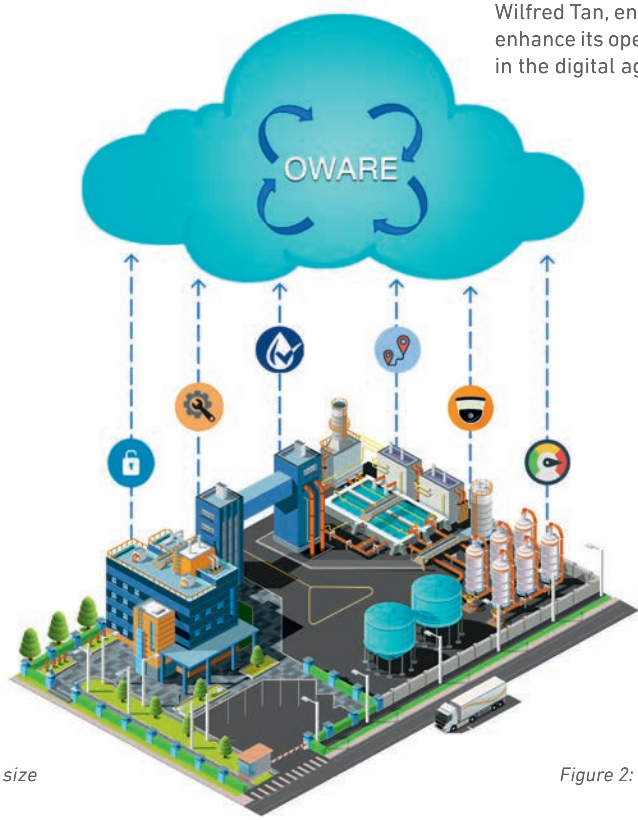

Figure 2: Illustration of OWARE platform

A digital twin for the Changi Water Reclamation Plant

A plant simulation model with predictive capabilities to test operational changes, improve operator training and more

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In recent years, there has been growing interest in the real-time control of operational systems and processes at used water treatment plants. However, there is currently lack of such simulation model that covers all operational aspects of used water treatment plants.

Researchers from Jacobs Engineering Group have partnered PUB to develop a whole-of-plant simulation model for the Changi Water Reclamation Plant (CWRP). The integrated model will combine real-time data pulled from Supervisory Control and Data Acquisition (SCADA) historian with software simulation packages (Replica™ and Sumo), coupling hydraulics, process and control systems into a single platform (Figure 1). Customised user interfaces will also be built into the model to further improve its functionality and maximise user experiences.

Through a secured connection to the SCADA system, the integrated model will replicate the properties of plant's components for data processing and data analysis. The data will be checked for outliers to ensure accuracy before being fed into Replica™ for hydraulics and control simulation, and Sumo for process simulation of the wastewater treatment plant.

In addition, the integrated model will continuously adjust its calibrations within defined ranges to match the plant's observed performance via machine learning. This will keep the simulations relevant to the real operations without requiring manual intervention from staff.

Since the simulation model runs independently of the actual system, it acts as a digital twin for operator training, that will help to facilitate knowledge transfer to new staff. Moreover, the simulation model can be used as an investigative tool to analyse the overall impact of operational change on plant performance without affecting actual plant operations, which is particularly useful when carrying out maintenance work. For example, if the operator had to lower the Solid Retention Time (SRT) in the bioreactor to take some volume out of service, the model would help to predict the impact on the secondary effluent quality and the impact of increased Waste Activated Sludge (WAS) production on thickening and digestion.

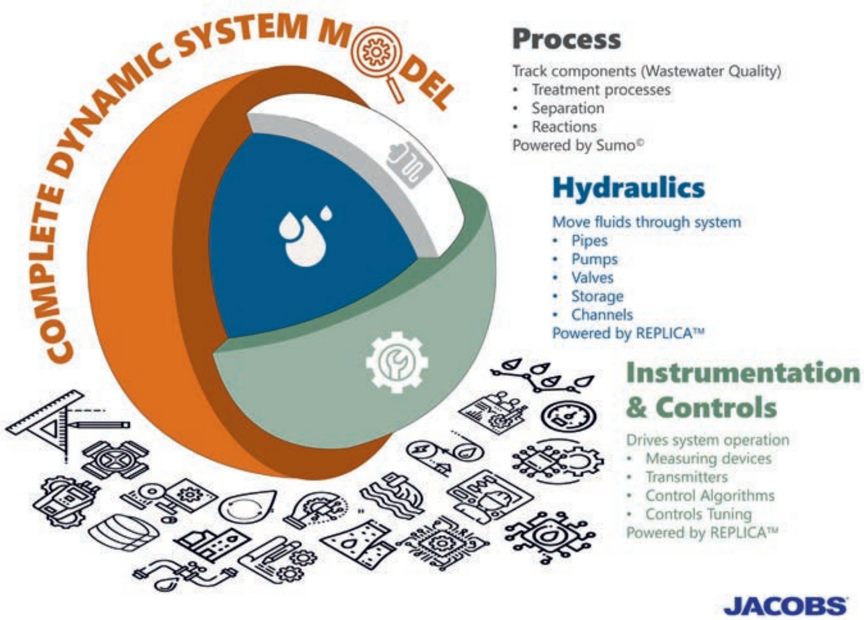

Figure 1: Development of a Complete Dynamic System Model

This model is expected to assist PUB in simulated scenarios to test and calibrate operational strategies to enhance the plant's water quality as well as optimise its energy and chemical consumption. The use of the model is also in line with PUB's goal of tapping smart technologies to increase productivity and improve resilience in operations.

"By using hi-fidelity dynamic simulation models, we can assess 'what if' scenarios in the digital domain and vet solutions prior to final implementation in the physical environment – a pivotal tool that will support PUB in improving operational performance," said Mr Raja Kadiyala, Global Director of Digital Solutions, Jacobs.

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

Digitalisation of operations and management of water reclamation plant with data-driven tools

Innovation by ST Engineering and Royal HaskoningDHV moves Singapore closer towards its smart nation vision

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Singapore's vision as a smart nation is driven by digital innovation that will transform the way its people live, work and play. As an urban city that is scarce in natural water resources, water reuse through digitalisation could be a critical step in ensuring water sustainability for the future.

Catalysing this vision are ST Engineering and Royal HaskoningDHV, which have joined forces to digitalise the operations and management of Ulu Pandan Water Reclamation Plant (UPWRP) via AquaNERVA and Aquasuite® systems respectively. These digital solutions aim to boost water security and quality at the UPWRP. UPWRP will be the first such facility in Singapore to benefit from these advanced technology solutions.

AquaNERVA, an in-house innovation of ST Engineering Marine, uses data analytics and machine learning techniques to perform condition monitoring, predictive diagnostics and prognostics (Figure 1 and 2). The technology has been tested extensively on major equipment on ships and proven successful to be applied at WRP to reduce equipment downtime and life-cycle cost through effective predictive maintenance.

AquaNERVA will be deployed at UPWRP to collect and analyse real-time data from key equipment. The smart system will be able to evaluate the equipment's condition and detect anomalies, alert operators to potential problems that could lead to

Figure 1: AquaNERVA for condition-based monitoring.

Figure 2: AquaNERVA prognostics.

failures, as well as recommend actions for repair and maintenance. Through machine learning techniques, AquaNERVA will also learn from past equipment failures and predict future ones more effectively.

Complementing AquaNERVA is the Aquasuite® system. It leverages predictive algorithms originally used in the Netherlands to predict drinking water flows and gauge wastewater flows at the UPWRP. The Aquasuite® system works by collecting real-time data on the plant's flows and qualitative measurements, including those for ammonia, phosphates, nitrates, oxygen and dry solids. The system uses this information to build a historical database. It will then make use of algorithms to predict the plant's wastewater flows and loads, oxygen needs, chemical dosing needs and other requirements (Figure 3 and 4).

The system can also detect abnormalities in the plant's processes and is capable of controlling key treatment processes, automatically optimising them in real-time based on its predictions and the plant's historical performance data. This will result in predictive rather than reactive control of the plant, leading to more stable and robust operations, better effluent quality, lower energy consumption and help enhance operators' productivity (Figure 5).

"It's very exciting to see the successes of these data-driven tools being applied to the UPWRP. This is not only a step towards fully-optimised operations and asset management that will enhance performance of this plant, but can potentially become the blueprint towards digitalising operations in all WRPs in Singapore, hurtling us towards our Smart Nation vision," said Mr Sim Chee Chong, Assistant Director of Marine Technology Solutions, Marine, ST Engineering.

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

Figure 3: An example of the Aquasuite® solution's flow prediction.

Figure 4: An example of machine learning in the Aquasuite® solution.

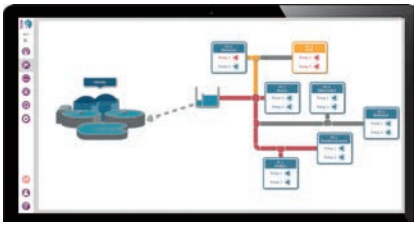

Figure 5: An example of how the Aquasuite® solution can optimise control of used water collection and treatment processes.

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.

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Online and near real-time monitoring of bacteria in water

Two new technologies increase water safety through near real-time bacteria monitoring in distribution networks

One of the most important tasks for all water utilities is to monitor the presence and growth of bacteria in their water networks. In Singapore, PUB does so through online monitoring of residual chlorine concentration in the distribution network. It also manually collects water samples and analyses them for bacteria.

However, these methods have their limitations. Online measurements of residual chlorine may not be representative of the actual dynamic changes in the total bacterial load. In addition, manual collection and analysis of samples for bacteria count is laborious and slow, with results available only after several days. As such, it is difficult to detect short-term bacteria dynamics in water samples during the day or week.

There are two separate ongoing projects that can potentially help PUB to achieve near real-time and online monitoring of bacteria in Singapore's water distribution network.

Harnessing flow cytometry

In 2012, scientists from the Swiss Federal Institute of Aquatic Science and Technology (Eawag) outlined a new online method to quickly and precisely detect and differentiate the total and intact bacterial cell count in water samples within 15 minutes by using flow cytometry. Their method involves staining the cells in a water sample with a fluorescent stain, and analysing the sample with a flow cytometer.

Recently, PUB partnered with onCyt Microbiology, an Eawag spin-off company, to test a fully automated online flow cytometry system at three different locations in PUB's potable water distribution network. For each location, the concentrations of total and intact bacteria were automatically measured every 20 minutes for four to five weeks, resulting in more than 10,000 high-resolution time series data collected.

The wealth of data makes it possible to quantify, study and understand short-term changes in water quality, and link observed dynamics in bacterial concentration and viability to operational practices and data from existing online sensors such as flow, residual chlorine, pH, and conductivity for the first time (Figure 1).

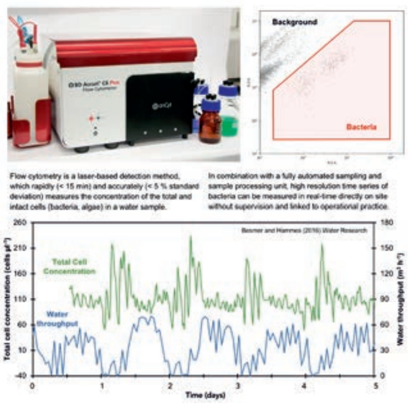

Figure 1: Online flow cytometry system for automated, direct sampling, sample preparation, and measurement of bacterial concentrations in water (top left). Typical graphical representation of one individual flow cytometry measurement showing every analysed cell (top right). Application example of a high-resolution time series showing how intermittent operation and temporary stagnation in a biological active carbon (BAC) filter result in fluctuating cell concentrations in final water.

This will enable more informed decisions about the need to optimise plant and network operations. The undertaken measures will also be more targeted and hence more time and cost-efficient. Furthermore, the impact of any optimisation can be directly checked with the flow cytometry system in real-time. This approach, together with more representatively chosen manual samples, further strengthens solid and modern, risk-based approaches to microbial water quality monitoring and management.

Tracking the dynamics of bacteria

In a separate project, PUB has installed Grundfos's BACMON bacteria sensors at three locations in PUB's potable water distribution network, similar to onCyt's flow cytometry system (Figure 2).

During the six-month project period, the installed sensors were able to track the dynamics in bacteria and abiotic particle concentrations in the distribution network. Subsequently, higher-than-normal readings were flagged out and investigated further in conjunction with other online water quality data.

Figure 2: Example of BACMON bacteria sensor installation along distribution pipe

"The BACMON solution uses a patented new technology to obtain 3D images of objects that are larger than around 300 nanometres in water and classify these as either bacteria or other particles. It can analyse the concentration of bacteria and other particles in the water within 10 minutes, thus offering a much shorter response time compared to current standard technologies (Figure 3)," said Mr Bo Højris, the lead product development engineer of Grundfos.

"BACMON has been extensively used in cooler climates in both chlorinated and non-chlorinated water with excellent results, and its use in Singapore has been smooth and required little maintenance. The results have opened a new window to the dynamics of bacteria throughout the distribution network," he added.

Figure 3: The BACMON sensor's online measurement of the absolute bacteria concentration level in the water.

An algal proliferation prediction system for Singapore's coastal waters

Using the prediction system to forecast harmful algal blooms, identify high-risk areas and take appropriate action

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Algal blooms can pose considerable threats to water management. They can foul membranes in water treatment plants, especially desalination plants, causing significant downtime and inconvenience as the membranes have to be replaced.

In Singapore's coastal waters, massive algal blooms can cause fish mass mortality events. Blooms of toxic algal species can also pose risks to human health, and result in severe illness or fatalities in extreme cases. For example, paralytic shellfish poisoning occurs when humans consume shellfish that fed on toxic algal blooms. To reduce such incidents, there is a need to develop a Harmful Algal Blooms (HABs) forecasting system.

Between 2015 and 2019, the National University of Singapore (NUS) Department of Civil and Environmental Engineering and Tropical Marine Science Institute partnered PUB to develop an integrated modelling and forecasting system for algal blooms in Singapore's coastal waters.

The team developed water quality forecast models for the East and West Johor Straits and early-warning algal bloom risk map capabilities for the West Johor Strait. This included identifying potential HABs triggers in the West Johor Strait by using historical data with ecological models and high temporal frequency data with data models. By integrating the model results into an operational response framework, PUB can identify potential HABs triggers and carry out algal bloom forecasts in the West Johor Strait (Figure 1).

"Our Algal Proliferation Prediction System (APPS) employs a mix of observations and deterministic and data-driven models. In doing so, it has shown the benefits of utilising such an integrated system for the forecasting of blooms in coastal waters as complicated as ours," said Dr Ooi Seng Keat, Head of the Ecological Monitoring, Informatics and Dynamics Lab, Tropical Marine Science Institute, NUS.

PUB officers were trained in marine algal identification and the use of the APPS to generate bloom risk maps to monitor coastal waters and assess the risk of algal blooms occurring. This allows PUB to take appropriate mitigation measures, if necessary, at an early stage.

Moving forward, the system can be automated and optimised to use real-time data to provide water quality forecasts. The bloom models for the East Johor Strait and Singapore Strait could also be included in the future to provide PUB with a more holistic view of the water quality and HAB status around Singapore.

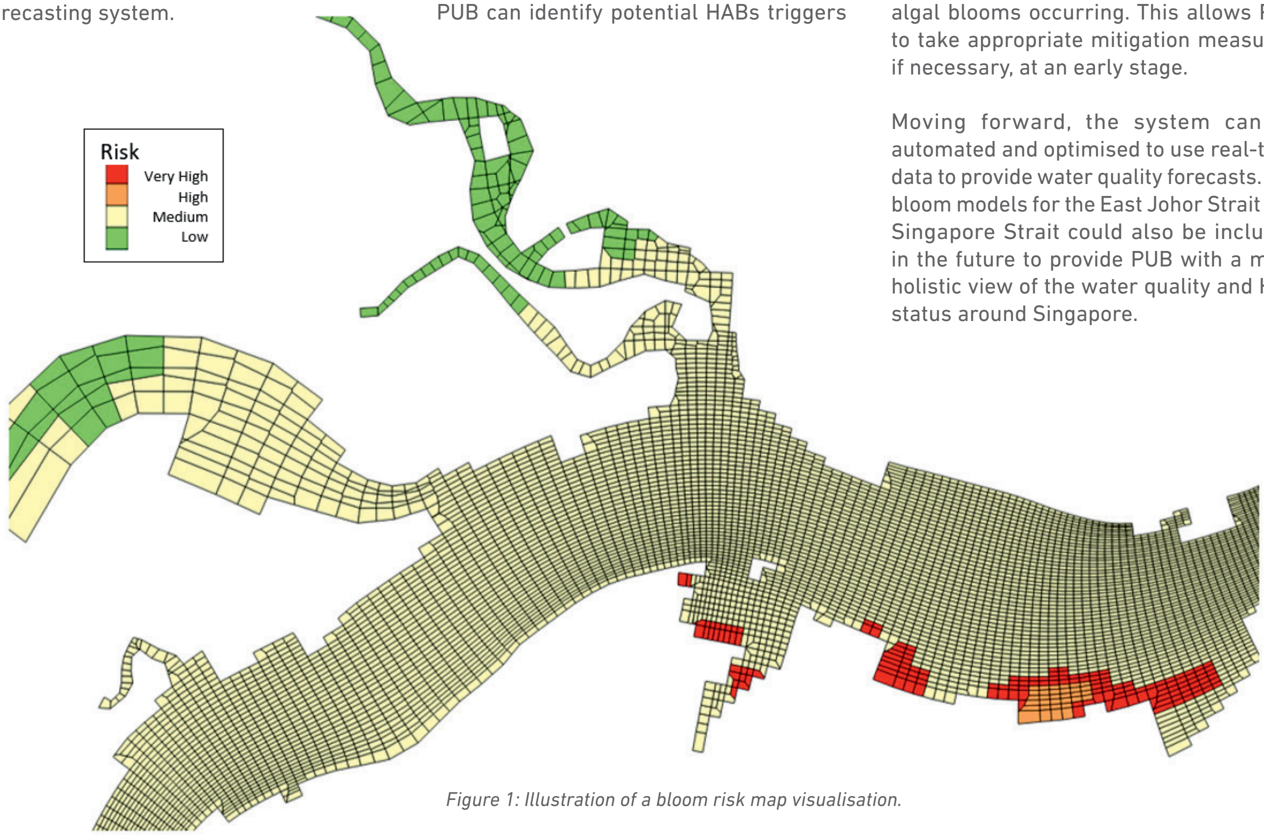

Figure 1: Illustration of a bloom risk map visualisation.

Testing a laser-based method for online detection of nanoparticles in water

The laser-induced breakdown-detection method flags distortions in water quality caused by nanoparticles

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PUB currently treats secondary effluent at its NEWater factories to produce high grade water for industrial and indirect potable use. There is a need to look into more efficient and sensitive water monitoring tools to sustain the quality of the treated water and ensure that no pathogen (which can be as small in size as nanoparticles) evades the water treatment process.

Technologiezentrum Wasser (TZW), the centre of applied research of the German Waterworks Association, is currently working with PUB on an ongoing two-year project to evaluate the use of laser-induced breakdown-detection (LIBD) as an online water monitoring tool for the NEWater factories. LIBD is one of the most sensitive analytical methods available for the online and continuous detection of nanoparticles in natural waters, capable of flagging out particles from 10 nanometres to about 1,000 nanometres.

The technology works by passing the water sample continuously through the device with a laser at constant laser pulse energy. Particles within the size detection range will break down due to the high laser pulse energy, causing the formation of an acoustical LIBD signal that can be monitored by the device. An increase in LIBD signal corresponds to an increase in concentration of nanoparticles in the water sample.

As the device provides immediate feedback on any distortion in water quality, it could also be used to monitor the integrity of microfiltration and ultrafiltration membranes, and to assess the efficiency of reverse osmosis (RO) membranes in removing particles for PUB's water treatment plants.

For this project, the LIBD device was transported from Germany to Singapore and installed at Kranji NEWater Factory (KNF) to carry out online measurements related to the feed and the permeate from the factory's phase 1 and phase 2 RO systems. The setup of the device is shown in Figure 1.

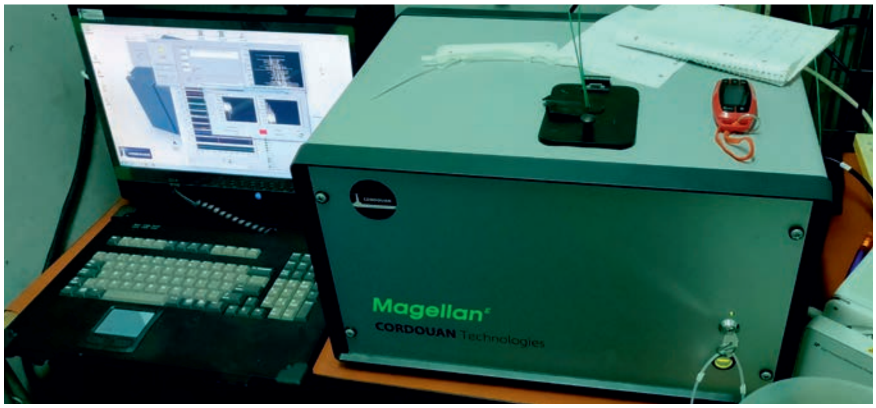

Figure 1: The laser-induced breakdown-detection (LIBD) device set up in the Kranji NEWater Factory (KNF).

The results show that the LIBD device can detect low nanoparticle counts in the permeate. It is also sensitive enough to evaluate the effectiveness of the RO treatment process in removing nanoparticles. The team noted that the measurements showed temporal changes in the permeate quality between day and night (Figure 2).

"If LIBD is able to detect events and correlate these to operational data and other analytical parameters that are regularly monitored in the permeate, it can be used as an online monitoring tool for membrane integrity. Additionally, it could also be applied as a monitoring parameter for the water quality of the permeate," said TZW's Dr Pia Lipp. She added that the team's evaluation of the plant data and correlation to the results of the LIBD device is still ongoing.

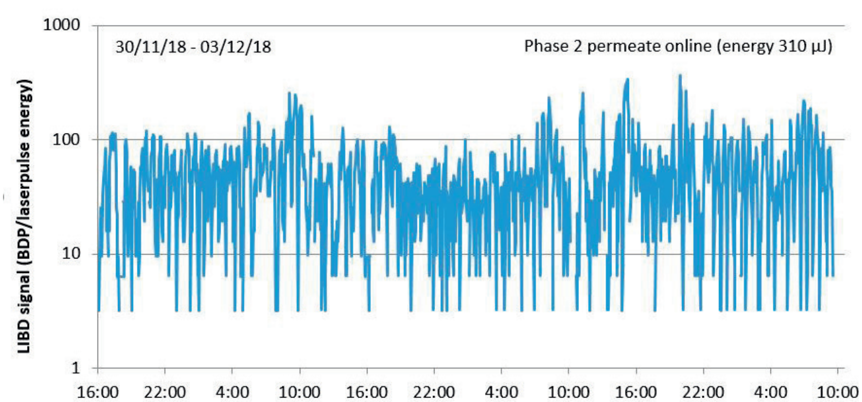

Figure 2: An example of the LIBD online measurement at KNF.

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.

Inspecting large diameter sewers with robots

A tethered robotic platform for inspecting underground sewers with constrained access

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Singapore's infrastructure to transport used water comprises sewers, a network of link sewers and the Deep Tunnel Sewerage System. As part of regular maintenance, robots are used to inspect the structural integrity of these tunnels and sewers.

Now, researchers from PUB and Nanyang Technological University (NTU) have developed a robotic system that could replace human staff in carrying out this work. Designed for the inspection of large-diameter sewers, it comprises an auxiliary power supply, a ground control station, a winch module and the robot itself.

The robot can fit through a 70 cm-diameter manhole, overcome tunnel floor deposits and fold its wheel frameworks to bypass obstacles in the tunnel. Its mechanical drive system has four hub motors, which eliminates the need for an external gearbox and transmission components, and it also has a front pan-tilt camera and a rear camera for navigation.

An inspection array mounted on the robot has three high-definition CCD cameras and four LED spotlights that can capture a nearly 270-degree view of the tunnel's interior surface above water. The cameras and spotlights have overlapping coverage to ensure seamless illumination and images, and an attendant algorithm can stitch the cameras' images to form a large flat map of the tunnel's surface.

With such maps, the detection of defects in the tunnel's surface can be automated, and changes in it tracked over time. In field trials conducted with Pipeline Services, a local contractor, the robot, which is tethered to the surface via a neutrally buoyant umbilical cable, was able to travel 205 m into the tunnel.

Now in the project's second phase, the researchers are developing a new robot that is able to fit through a 60 cm by 60 cm manhole and travel at least 400 m. "The depth of the service tunnels can be up to 50 meters with distances between adjacent access points spanning 500 m to 2 km," explained NTU's Professor Gerald Seet.

He said: "Deploying robots into sewer systems is not without its engineering and technological challenges, for example the restrictions to access through manhole openings and the issue of how to keep the robots supplied with power. In addition, the proposed system needs to consider the robot's extraction in the event of component failure. But it benefits from a reduced level of risks to humans from prolonged incursions into a potentially hazardous environment."

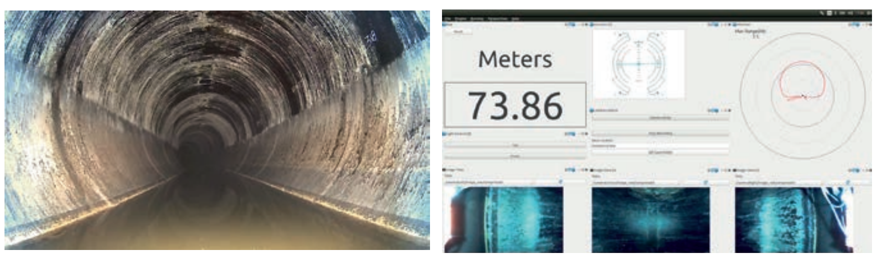

Figure 2: The front pan-tilt-zoom (PTZ) camera view (left) and the user interface with three images from the robot's inspection array (right).

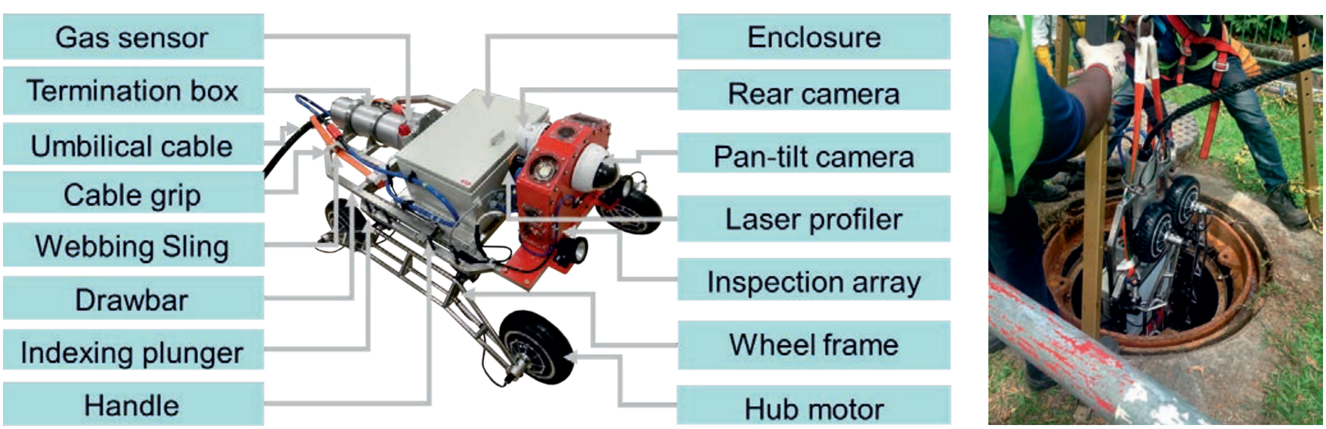

Figure 1: The robotic platform in compact configuration (left) and when accessing a sewer opening (right).

An unmanned aerial vehicle to inspect Singapore's Deep Tunnel Sewerage System

A customised drone with advanced sensors and computational intelligence to fly in tunnels and capture inspection data autonomously

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With more than a decade of usage under its belt, Singapore's used water superhighway, the Deep Tunnel Sewerage System (DTSS) Phase 1 requires regular inspection for preventive maintenance. Using a miniature unmanned aerial vehicle (UAV) with smart sensors for this task is beneficial for two reasons – our contractors do not need to enter a potentially hazardous environment, and the UAV can easily carry out its work without contact with the used water or the tunnel's walls.

However, the DTSS environment is challenging for a UAV because Global Positioning System signals cannot penetrate into it. The tunnel is long, space-constrained and completely dark. Furthermore, its entry and exit shafts are situated in unusual positions.

Figure 1: The design of the multi-sensory unmanned aerial vehicle (UAV).

UAV developer AeroLion Technologies has been working with PUB to design and develop a UAV that can overcome these issues. In the first phase of the project, the team custom-made a UAV platform with multiple on-board sensors, specific depth cameras, omnidirectional camera, range finders, accelerometer, gyroscope, barometer, magnetometer and methane gas detector (Figure 1). Illumination LEDs were also built into the platform to allow sufficient lighting for its cameras to work in the pitch-black environment.

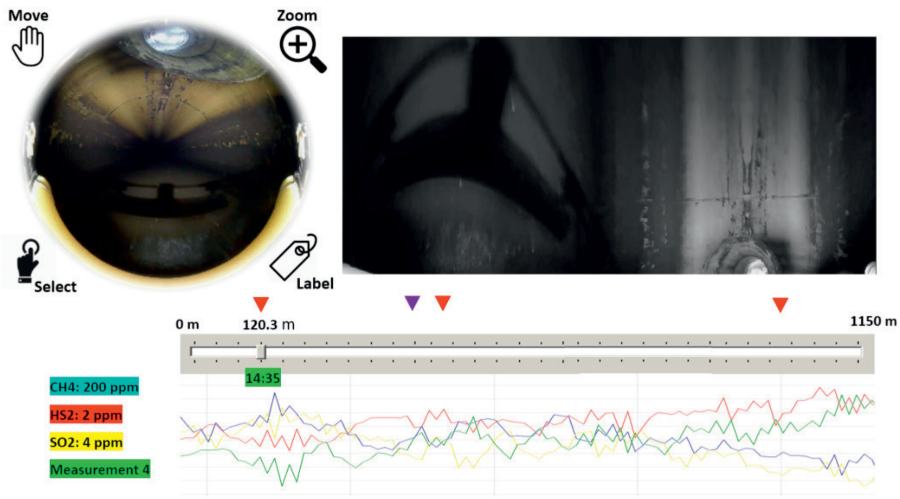

Figure 2: Automated generation and visualisation of the UAV's inspection results.

Beyond the hardware, the team also developed real-time three-dimensional navigation algorithms that would work based on the depth cameras' sensing, and programmed them into the UAV's on-board miniature computer. An innovative launch and retrieval mechanism was also designed so that the UAV could be safely launched and retrieved from the bottom of a vertical shaft. In another inspired touch, the mechanism also acts as a communication relay between the UAV and an external Ground Control Station to solve the non-line-of-sight issue.

In field tests, the UAV platform was flown successfully in both a DTSS side tunnel and a DTSS main tunnel, via an offset shaft and a direct shaft respectively. It also achieved a minimal localisation error of just two percent with regard to its total distance travelled.

Moving towards the second phase of the project, the team will look into addressing some engineering and manufacturing issues, improve the UAV's location tagging accuracy and expand the variety and quality of its data collection. Part of this will be done through the addition of more gas sensors and a light detection and ranging (LIDAR) sensor.

The team will also develop more advanced image and data analytics to facilitate automated generation and visualisation of the inspection results (Figure 2). Lastly, the UAV's efficiency, convenience and safety can be improved further.

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

LIST OF ABBREVIATIONS, ACRONYMS, SYMBOLS & UNITS

Acronyms & abbreviations

AI	Artificial Intelligence
ALS	Automated Laboratory System
AMR	Automated Meter Reading
AOP	Advanced Oxidation Process
APPS	Algal Proliferation Prediction System
BAC	Biological Active Carbon
CCKWW	Choa Chu Kang Waterworks
CRP (Water)	Competitive Research Programme (Water)
CWOS	Catchment and Waterways Operations System
CWRP	Changi Water Reclamation Plant
DaC	Data-Centric
DeC	Design-Centric
DTSS	Deep Tunnel Sewerage System
Eawag	Swiss Federal Institute of Aquatic Science and Technology
EWTCOI	Environmental & Water Technology Centre of Innovation
HABs	Harmful Algae Blooms
ICs	Intelligent Checkers
IFC	Imaging Flow Cytometry
IFCB	Imaging FlowCytoBot
IoT	Internet-of-Things
IVP	Integrated Validation Plant
IWSDF	Industrial Water Solutions Demonstration Fund
KNF	Kranji NEWater Factory
LED	Light-Emitting Diode
LIBD	Laser-Induced Breakdown-Detection
LIDAR	Light Detection and Ranging
MES	Micro-Electrochemical Sensor
NERI	NUS Environmental Research Institute
NGOs	Non-Governmental Organisations
NRF	National Research Foundation
NTU	Nanyang Technological University
NUS	National University of Singapore
NUSwan	New Smart Water Assessment Network
OWARE	Object Awareness
PLCs	Programmable Logic Controllers
PRO	Pressure Retarded Osmosis
PTZ	Pan-Tilt-Zoom
PUB	PUB, Singapore's National Water Agency
R&D	Research & Development
RFP	Request-For-Proposals
RMSE	Root Mean Square Error
RO	Reverse Osmosis
SAM	Sampling and Adaptive Monitoring
SCADA	Supervisory Control and Data Acquisition
SGP	Sparse Gaussian Processes
SgWX	Singapore Water Exchange
SMEs	Small and Medium Enterprises
SRT	Solid Retention Time
START	Separation Technologies Applied Research & Translation
SWaT	Secure Water Treatment
TMSI	Tropical Marine Science Institute
TRLs	Technology Readiness Levels
TZW	Technologiezentrum Wasser
UAV	Unmanned Aerial Vehicle
UPWRP	Ulu Pandan Water Reclamation Plant
VOC	Volatile Organic Compound
VR	Virtual Reality
WADI	Water Distribution
WAS	Waste Activated Sludge
WaterWiSE	Water Wireless Sentinel
WHOI	Woods Hole Oceanographic Institution

Symbols & units

cm	Centimetre
m^3	Cubic metre
$m^3\ h^{-1}$	Cubic metre per hour
m^3/mth	Cubic metre per month
km	Kilometre
kWh/m^3	Kilowatt-hour per cubic metre
m	Metre
μJ	Microjoule
μl	Microlitre
mgd	Million (imperial) gallons per day
min	Minute
ppm	Parts per million
s	Seconds

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