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WATER: FROM SCARCE RESOURCE TO NATIONAL ASSET

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URBAN SYSTEMS STUDIES

WATER: FROM SCARCE RESOURCE TO NATIONAL ASSET

CENTRE for LiveableCities SINGAPORE

Second Edition, Singapore, 2020

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CENTRE for LiveableCities SINGAPORE

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Set up in 2008 by the Ministry of National Development and the Ministry of the Environment and Water Resources, the Centre for Liveable Cities has as its mission "to distil, create and share knowledge on liveable and sustainable cities". The Centre's work spans four main areas—Research, Capability Development, Knowledge Platforms, and Advisory. Through these activities, the Centre hopes to provide urban leaders and practitioners with the knowledge and support needed to make our cities better. For more information, please visit www.clc.gov.sg.

Research Advisors for the Centre's Urban Systems Studies are experts who have generously provided their guidance and advice. However, they are not responsible for any remaining errors or omissions, which remain the responsibility of the author(s) and the Centre.

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Cover photo:
The Kallang River at the Bishan-Ang Mo Kio Park is PUB, Singapore's Water Agency's Active, Beautiful, Clean Waters (ABC Waters) flagship project that showcases the transformation of water into an environmental asset. Image courtesy of Jon Chiang.

CONTENTS

FOREWORD

Over the last few decades, Singapore has successfully transformed itself from a fledgling independent state into a modern metropolis. Since independence, Singapore has been ahead of its time in prioritising issues concerning the environment and water and placing them high on the national agenda. As our first Prime Minister, Mr Lee Kuan Yew, said, "Every other policy has to bend at the knees for our water survival." This attested to the government's commitment to ensuring Singapore's water sustainability.

The Singapore of today has an excellent water management system in place that ensures a robust and diversified water supply through our Four National Taps, namely local catchment water, imported water, NEWater—Singapore's brand of reclaimed water—and desalinated water. However, our water journey has been all but smooth.

Despite an abundant average rainfall of 2,200 mm/year, there were insufficient catchment areas to capture and store the rainwater in the 1970s. The water shortage was exacerbated by the polluted waterways that rendered rainwater flowing in them unfit for treatment for drinking purposes. The open sewers, poor sanitation and seasonal floods further compounded the pollution problem.

The Water Urban Systems Study succinctly captures how Singapore was able to turn its water constraints into a virtue, highlighting the three key principles that underpinned the efforts of PUB, Singapore's National Water Agency, in ensuring water sustainability—Collect every drop of rainwater, Collect every drop of used water, and Reuse every drop of water more than once. These principles have successfully been translated into results through the government's financial prudence, foresight to plan ahead, commitment to meticulous implementation, and strong support from the people, public and private sectors.

These would be the same principles that we would draw upon to face the challenges that Climate Change would bring to our water supply system. Rainfall extremes would require a re-assessment of the yield of our reservoirs, and rising sea levels with storm surges would call for greater protection for our estuarial reservoirs against sea water ingress. These are long term challenges for which work would have to begin soon.

I hope that through this Water Urban Systems Study, readers will gain a better appreciation of the foresight, tenacity, ingenuity and strong public support that enabled Singapore to successfully close the water loop and provide water for all.

Tan Gee Paw
Former Chairman
PUB, Singapore's National Water Agency

PREFACE

The Centre for Liveable Cities' research in urban systems unpacks the systemic components that make up the city of Singapore, capturing knowledge not only within each of these systems, but also the threads that link these systems and how they make sense as a whole. The studies are scoped to venture deep into the key domain areas the Centre has identified under the Singapore Liveability Framework, attempting to answer two key questions: how Singapore has transformed itself into a highly liveable city over the last five decades, and how Singapore can build on our urban development experience to create knowledge and urban solutions for current and future challenges relevant to Singapore and other cities through applied research.

The research process involves rigorous engagement with our stakeholder agencies, and numerous oral history interviews with Singapore's urban pioneers and leaders to gain insights into development processes. The tacit knowledge drawn out through this process allows us to glean useful insights into Singapore's governance and development planning and implementation efforts. As a body of knowledge, the Urban Systems Studies, which cover aspects such as water, transport, housing, industrial infrastructure and sustainable environment, reveal not only the visible outcomes of Singapore's development, but the complex support structures of our urban achievements.

Water: From Scarce Resource to National Asset is a revised edition of one of the first titles in the Urban Systems Studies series.

The Centre is pleased to publish this revised edition and would like to thank PUB, Singapore's National Water Agency, and all those who have contributed their knowledge, expertise and time to make this publication possible. I wish you an enjoyable read.

Khoo Teng Chye
Executive Director
Centre for Liveable Cities

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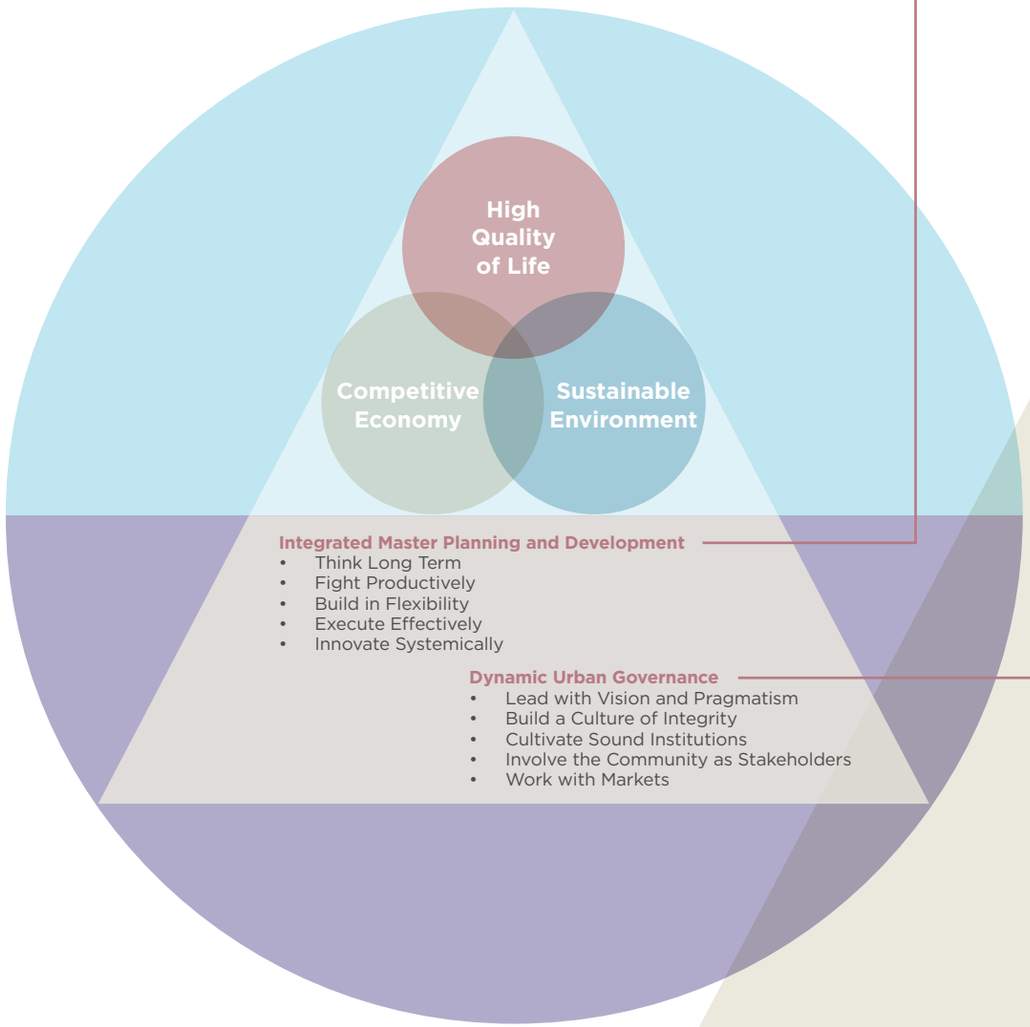
We would also like to thank Mr Tan Gee Paw for his advice and foreword, Mr Ng Joo Hee for contributing the post-script, and PUB, Singapore's National Water Agency, for their advice, inputs and support to this publication.

THE SINGAPORE LIVEABILITY FRAMEWORK

The Singapore Liveability Framework is derived from Singapore's urban development experience and is a useful guide for developing sustainable and liveable cities.

The general principles under **Integrated Master Planning and Development** and **Dynamic Urban Governance** are reflected in the themes found in *Water: From Scarce Resource to National Asset.*



Integrated Master Planning and Development

Think Long Term

Singapore has "closed" the water loop by reclaiming used water for further use. This high-grade reclaimed water is NEWater. Together with desalination, Singapore has built up a sustainable and diversified supply of water.

(See The Water Loop, page 28)

Innovate Systemically

The Deep Tunnel Sewerage System (DTSS) was conceptualised in the mid-1990s. The award-winning and highly innovative sewerage system now conveys used water from homes and industries through a long and deep underground tunnel sewer to a centralised water reclamation plant at Changi; the DTSS has made it possible for efficient large-scale water recycling. It also frees up valuable land space in Singapore that otherwise might have been taken up by existing reclamation plants and intermediate pumping stations.

(See Sewers, page 33)

Dynamic Urban Governance

Lead with Vision and Pragmatism

The government saw the importance of transforming the polluted Singapore River into clean and functioning water catchments. Cleaning up the Singapore River would also boost the business environment and quality of life. In 1977, former Prime Minister (PM) Lee Kuan Yew set the Ministry of the Environment a target of ten years to make the river clean enough for fishing. Under his leadership, PM Lee provided his full political support and entrusted the experts to manage the river clean-up project.

(See Cleaning the Singapore River—Providing Alternatives, Managing Trade-offs, page 16)

Cultivate Sound Institutions

To ensure a well-integrated water management system, the Public Utilities Board (PUB) was re-organised in 2001—the Sewerage and Drainage Departments of the Ministry of the Environment and the Water Department of the PUB were merged into PUB, Singapore's National Water Agency, which would be in charge of all operational nodes of the water loop.

(See The Water Loop, page 28)

Involve the Community as Stakeholders

Recognising that NEWater would be an important source of water supply for Singapore, the PUB embarked on an extensive public education and outreach programme involving international experts, grassroots leaders and politicians. This proved crucial in securing the public's acceptance of recycled used water.

(See Getting Past NEWater's "Yuck Factor"—Bringing the Public On Board, page 24)

OVERVIEW:

THE JOURNEY FROM SCARCITY TO SUSTAINABILITY

Singapore, a small island city-state in Southeast Asia, receives an average rainfall of 2,200 mm a year, abundant by most standards, yet it also ranks as one of the countries most likely to be water-stressed by 2040.[1] This may seem ironic, but it is not surprising. Singapore does not have much groundwater to begin with nor many natural freshwater bodies, and its compact 725.1 km^2 landmass[2] puts a limit on the amount of land that can be allocated to capture and store rainwater. To boot, since the turn of the 20th century, the needs of an ever-growing population and an expanding economy have consistently put a squeeze on the already scarce land available for protected water catchments.

In the 1960s, ensuring a stable and adequate supply of water was a key challenge for the Singapore government. It was not always able to meet the demand for water, which was around 77 million gallons a day (mgd). The waterways in Singapore were polluted and the protected water catchments did not have enough reserves to tide the country over prolonged dry seasons. Despite buttressing the domestic water supply with water imported from neighbouring Malaysia, there were still periods of drought. Water rationing was imposed in 1961 and again from May 1963 to January 1964.

Another cut in water supply

SINGAPORE, Mon.—Singapore's 12 hour water supply will be curtailed by two hours from next Monday, if by then water stocks are still below the danger level of 33 per cent. Dr. Fong Kim Heng, chairman of the Public Utilities Board, announced this today.

The present 12-hour "off" period from 8 a.m. to 8 p.m. was introduced in April. From Monday supplies will be off from 6 a.m. to 8 p.m.

An appeal

Dr. Fong appealed to the public to cut down consumption by 10 to 15 per cent to conserve water stocks around the 33 per cent level.

He listed these ways in which the public could help to conserve water:

- By using their WCs to a minimum;
- Washing clothes less often;
- Factories and establishments who have been exempted from rationing

★ See Back Page—Col. 1

Rainmaking attempts to resume next week

★ From Page One

for special reasons to cut down consumption.

Dr. Fong also appealed to those in the rural areas "not to be selfish" by extending hoses from standpipes to their houses or by washing clothes with a continuous flow from the pipe.

He announced that cloud-seeding operations under the Senior Meteorological Officer, Mr. Hwang Tiaw Sool, would begin early next week.

A Cessna aircraft, chartered from Malaysia Air Charter Company is now being fitted with rainmaking equipment.

Water stocks have dropped a further 0.8 per cent over the weekend to 32.4 per cent — the lowest recorded during this period of rationing.

A news article published on 27 August 1963, informing the public about water scarcity and the need for water rationing.

Fifty years on, the challenge and limitations of geography remain. Yet since 1979, access to clean water in Singapore has been 100%. This is despite the fact that overall water demand has grown more than sevenfold to about 430 mgd between 1960 and 2018.[3] The government has been able to meet this demand through the four sources of water that PUB, Singapore's National Water Agency—the government agency responsible for water management—calls the "National Taps", namely, water from local water catchments (e.g., reservoirs), imported water from Malaysia, reclaimed water known as NEWater, and desalinated water.

Today, Singapore's sustainable water supply is the result of a tightly integrated water management system that uses advanced technology to mitigate Singapore's physical limitations. Yet the philosophy behind this system can be put quite simply—every drop of rain that can be captured should be captured, and every drop of wastewater that can be safely reclaimed should be reclaimed. The collection of rainwater in the catchments, the treatment and distribution of drinking water, the sewerage and drainage systems, and the production of NEWater and desalinated water are all part of the water loop (see Timeline: Key Water Milestones on page 64).

As Singapore moved from a situation of water scarcity to sustainability (see Appendix 1 for some of the key governance tools of Singapore's water management system), the governance of Singapore's water management policies has evolved over the last six decades along with the changes in the political context and national priorities. For sure, water remains an important national security matter. In the early days policy initiatives were very much politician-driven and top-down; these days, with the threat of a critical water shortage decreased and with water management systems in place, they are more institution-driven. Where the management of Singapore's water resources had once been the sole domain of the government, the private sector and community can now take, and are encouraged to take, a more active role.

CHAPTER 1

THE EARLY DAYS OF WATER MANAGEMENT

> "Every other policy has to bend at the knees for our water survival."

Lee Kuan Yew[4]

Singapore was a British colony from 1824 until 1959, when it became self-governed. In 1963, it merged with Malaya, Sabah and Sarawak to form Malaysia but separated after only two years. At that point, one of the first things that weighed on then-Prime Minister (PM) Lee Kuan Yew's mind was how he could ensure that the newly independent country would have enough water to survive. The separation was far from amicable—Singapore had been expelled from the federation—and Singapore was heavily reliant on Malaysia for its water.

Drinking water was supplied to rural areas via water wagons during the dry season in 1959.
Image from the Ministry of Information and the Arts Collection, courtesy of the National Archives of Singapore.

This dependency dated back to colonial times when Singapore started importing water from Johor, a state in Malaysia, through a 1927 agreement. The main domestic water sources—MacRitchie, Peirce and Seletar reservoirs—had not been able to provide enough water for the needs of a growing population and industry. Two years after Singapore achieved self-governance, the City Council of the State of Singapore signed an agreement with the State of Johor in Malaysia in 1961 to give Singapore the full and exclusive right and liberty to take, impound and use all the water within the Gunung Pulai and Pontian catchments, and in the Tebrau and Scudai Rivers until 2011.[5] A second agreement was signed the following year for the supply of up to 250 million gallons a day (mgd) of water from the Johor River until 2061.[6] These became known as the 1961 and 1962 Water Agreements. However, even with water imported from Malaysia, Singapore still suffered from water shortages and had to resort to water rationing in the 1960s.

Before separation, PM Lee had made sure that the two Water Agreements were guaranteed by both the Singapore and Malaysia governments in the 1965 Separation Agreement, which established Singapore as a sovereign state, and was lodged at the United Nations. Despite the presence of this legal safeguard, PM Lee was told that on the very day of Singapore's independence, Malaysia's first Prime Minister, Tunku Abdul Rahman, had said to the British High Commissioner in Kuala Lumpur, "If Singapore doesn't do what I want, I'll switch off the water supply."[7]

As such, almost immediately after Singapore had gained independence, PM Lee called up Lee Ek Thieng, then-Chief Engineer of the Public Utilities Board (PUB), which had been set up in 1963, to ask him if Singapore could achieve water sustainability by capturing every drop of rain on the island.[8] PM Lee's question to the PUB was pertinent. Singapore had an average rainfall of 2,200 mm a year but had been unable to capture much of this water. The main rivers were not suitable catchments as the rainwater collected was quickly contaminated by the large amounts of sewage and other pollutants that spilt into these rivers.

Apart from ensuring a more stable water supply for domestic and industrial use, the ruling government also had another motivation for cleaning up the rivers. The polluted waters, poor drainage and open sewers meant that there were parts of Singapore that stood in stark contrast to the beautiful areas where the British used to live. For political reasons, there needed to be a more uniform standard of liveability across the island.[9]

Flood at Opera Estate in December 1969.
Source: The Straits Times © Singapore Press Holdings Limited. Reprinted with permission.

As it turned out, Singapore would have to wait another decade for advancements in technology that made cleaning these rivers feasible. For the time being, the PUB's only option was to dam as many small streams as possible to capture whatever rainfall it could.

Strong leadership would be critical to drive water management initiatives at a time when the government had to address other priorities, for instance, the economy and the housing situation. As a reflection of the importance the government placed on Singapore achieving water sustainability, Singapore's water policy was coordinated out of PM Lee's office for the 31 years that he was Prime Minister.

The Water Planning Unit was set up in 1971 in the Prime Minister's Office to complement the work of the PUB. Lee Ek Tieng headed this unit and assisted by a young engineer, Tan Gee Paw, drew up Singapore's first Water Master Plan in 1972. Over the next four decades, these two men worked closely and were the key bureaucrats who led the major initiatives that shaped the water management system Singapore has today.

The 1972 Water Master Plan stipulated that Singapore had to meet 75% of its water demand using its own water supply. This was to ensure that daily life could carry on without serious disruption should the supply of water from Johor fall or be cut off. This percentage, however, quickly proved far from sustainable as domestic and industrial needs grew.[10] In addition, the government had to tackle a second water-related challenge. Flooding was a common occurrence in the low-lying areas (30% of Singapore was less than five metres above the sea level), especially when intense rains coincided with high tides.[11] Indeed, less than five years after independence, Singapore would experience one of its most serious floods. Following heavy rains in December 1969, 29 areas were flooded, with some stretches of road submerged under two metres of water. Five people died. The flood damage was then estimated at S$4.3 million.[12]

Guided by this master plan, Singapore went through a phase of expansion and construction to increase water supply, improve sanitation and reduce flooding from the late 1960s through to the 1980s.

Floods, unleashed by the heaviest rainfall ever recorded in a single day, swamped Singapore for two days in December 1978.
Source: The Straits Times © Singapore Press Holdings Limited. Reprinted with permission.

To increase the water supply, the PUB expanded the capacities of the Seletar and Peirce reservoirs in 1969 and 1975, respectively. At Seletar Reservoir, it set up a system to abstract raw water from seven adjacent streams, and this water was pumped into the reservoir. At Peirce Reservoir, a higher dam was constructed upstream from the existing dam to increase the storage capacity of the reservoir.

> *Those were the days when we were trying to get people to come to Singapore, the investments—JTC [Jurong Town Corporation] was going at a really frantic pace. HDB [Housing & Development Board], of course, was a boomtown because we were trying to break this problem in housing. Ang Mo Kio came in, then Bishan and so on. And every one of them, I said, was potentially a flood problem for us.*[13]

The Public Works Department (PWD) developed the Sewerage Master Plan (later renamed the Used Water Master Plan) in the late 1960s. It was necessary as the sewerage system needed to cope with the strains that a growing population, construction of public housing, industrial development in Jurong and the redevelopment of the Central Area would put on it. In 1971 only 57% of the population was served by the main public sewerage network. The rest depended on the nightsoil collection

Nightsoil carriers in the 1980s.
Image courtesy of the National Archives of Singapore.

Nightsoil carriers collecting human waste that were deposited in buckets.
Image from the Ministry of Information and the Arts Collection, courtesy of the National Archives of Singapore.

system or some other sewerage system.[14] The PWD made plans for a rapid expansion of the sewerage network, the relaying and re-routing of existing services, and the expansion of sewage treatment works. It divided the island into six used water catchment zones, each served by a water reclamation plant, and adopted the practice, in compliance with international standards, of discharging treated effluent from the plants into the sea.

The Drainage Department was set up under the Ministry of the Environment in 1972 to manage stormwater for flood prevention and alleviation. The Drainage Department, working with the Urban Redevelopment Authority and the HDB, developed a Drainage Master Plan in the 1970s. As Singapore developed, tracts of land were carved up for construction projects and as a result, more stormwater was conveyed into the drainage system. Areas, where the drainage system could not clear the water fast enough, became flood-prone. In particular, Bukit Timah and Opera Estate experienced severe flooding.

Given that land had to be used for roads and buildings, there was a limit to the size of drains and canals that could be built. In some cases, the PWD resorted to practical solutions like having covered drains, and in others, it came up with innovative systems like the underground detention tank that was used in Opera Estate.

To ensure that new land developments made adequate provisions for the drainage system, the administrative procedures for planning and building control, which were under the purview of the Planning Department at the Ministry of National Development, required that the Drainage Department had to be consulted on the technical requirements for drainage. This had to be done at every stage of any new development proposal, and the Drainage Department was responsible for imposing drainage requirements in line with the Drainage Master Plan.

All this early work done to improve the management of sewers and drains would have an important impact on Singapore's water supply in the late 1990s when Singapore began to take a serious look at water reclamation as a source for potable water.

CHAPTER 2

WATER SUPPLY— TOWARDS WATER SUSTAINABILITY

> "Today, we talk about our Four National Taps as if setting them up was as easy as building roads or houses. Be assured that it was not."

Goh Chok Tong[15]

THE FOUR NATIONAL TAPS

Singapore's water sources are called the "Four National Taps". For a long time, the country relied on only two National Taps—local catchment water and imported water from Malaysia. Although the 1972 Water Master Plan had recommended looking at non-conventional sources such as water reclamation and desalination, these options were put on the back burner due to high cost and uncertainty about the technology. It was only in the mid-1990s that the government, in part pushed by political developments and by improvements in the reliability and cost-efficiency of membrane technology, began to revisit the idea of developing alternative water sources that would later become Singapore's third and fourth National Taps.

The First National Tap—Domestic Sources

Singapore's domestic sources of water come from its network of reservoirs and waterways, including the protected catchments like MacRitchie, Peirce and Seletar reservoirs. As Singapore developed, the land needs of the growing population and industry meant that there was less land that could be spared for additional protected water catchments. This situation compelled the government to create unprotected catchments and later, urban catchments.

In 1975, the first unprotected catchment was created by damming the Kranji, Pandan, Murai, Poyan, Sarimbun and Tengeh rivers to create new reservoirs.[16] Compatible and less pollutive land use developments—such as residential estates and light industry—were allowed near these unprotected catchments.

The tension between land use for water catchments and housing would grow. In the early 1980s, the Housing & Development Board (HDB) was issued a directive to deliver 140,000 new flats between 1982 and 1985. New towns were proposed in areas that were unprotected water catchments, such as Bedok and Sungei Seletar. After a long, drawn-out negotiation, the Ministry of National Development (MND), HDB and Ministry of the Environment (ENV) agreed on a water catchment policy that the Cabinet endorsed in 1983. The policy allowed the public and private sectors to develop land in unprotected water catchment areas up to an "urbanisation cap" of 34.1%. This cap excluded the water surface area and was subject to a pollution density limit of 198 dwelling units per hectare and adherence to pollution control.[17]

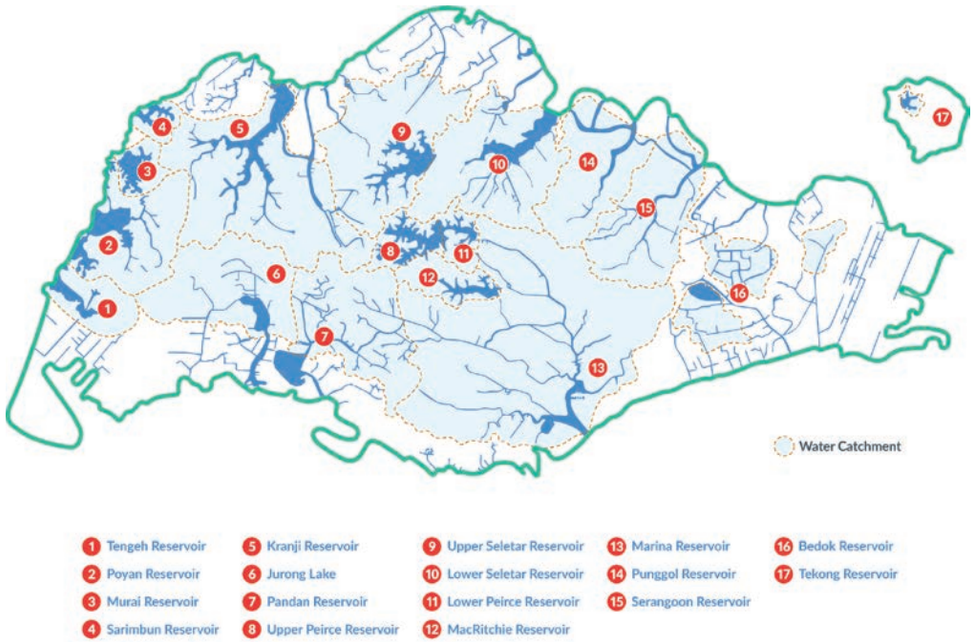
The first urban catchment was the Sungei Seletar-Bedok Water Scheme that was completed in 1986. Pig farms were phased out from the Sungei Seletar area and the farmers were given resettlement compensation. At Bedok, which was less developed, the ENV and the HDB tightened pollution control through various guidelines and policies. The Urban Redevelopment Authority (URA) allocated most of the land in the catchments to public housing and light industry. Bedok Reservoir was built out of a sand quarry that the HDB had used for its housing projects. Water from the network of drains in Bedok fed the reservoir. Since its inception, the water from the Sungei Seletar-Bedok Water Scheme has consistently been assessed to be as good as that obtained from protected catchments.

Singapore had been fortunate as the British colonial government had left a valuable engineering legacy—the separation of the stormwater and used water systems, which formed the foundation of Singapore's water management policy. This ensured that the inland waterways, reservoirs and the sea surrounding Singapore were not polluted through the indiscriminate discharge of untreated or semi-treated used water

and trade effluent. It also prevented stormwater from entering the used water systems that could cause overflows. Because of this system, PUB, Singapore's National Water Agency, was able to harvest rainwater from the urban areas and develop water catchment areas in the urban zone.

Across the country, the government cleaned up polluted waterways so that they could be functioning water catchments. The most significant and ambitious project was the clean-up of the highly polluted Singapore River and Kallang Basin that began in 1977. Together, these two catchments made up 30% of Singapore's land area in the 1970s. Many Singaporeans lived along the rivers, and human activities on the waterfront, together with a lack of proper sewage facilities and discharge control, had turned the rivers into open sewers. With office towers, hotels and a new central business district being built, there was an urgent need to clean up these waters.[18] In 1977, then-Prime Minister (PM) Lee Kuan Yew challenged the ENV to make the rivers clean enough for fishing. He promised to give each officer a gold medal if the clean-up was successful. "His [PM Lee] objective was very clear—clean up the Singapore River," said Lee Ek Tieng, "though he never told you how to clean it up. He leaves it to the engineers to go and do it, and he gives his full political support."[19] The clean-up was completed in 1987 (see Box Story, page 16). Two decades later, the cleaned-up Singapore River would become a key urban catchment that fed into Marina Reservoir.

In 1999, the urbanisation cap of 34.1% in unprotected catchment areas was lifted, following a study that showed that the water quality in the reservoirs had not deteriorated significantly despite development in these catchment areas. In 2002, the National Environment Agency (NEA) and the PUB led a review of the catchment policy. The PUB, Jurong Town Corporation (JTC) and Economic Development Board (EDB) agreed upon a negative list of 18 industries that would not be allowed to set up near the catchments. "Strategic industries" that were on the list but considered vital to the economy were given special exemption to be sited in the catchments if there were no suitable sites elsewhere and anti-pollution guidelines were met. In 2007, the negative list was extended to cover other unprotected catchments as well. (See Appendix 2 for a more detailed timeline on the Water Catchment Policy.)



The blue shaded parts of this map represent Singapore's water catchment areas and reservoirs.
Image courtesy of PUB, Singapore's National Water Agency.

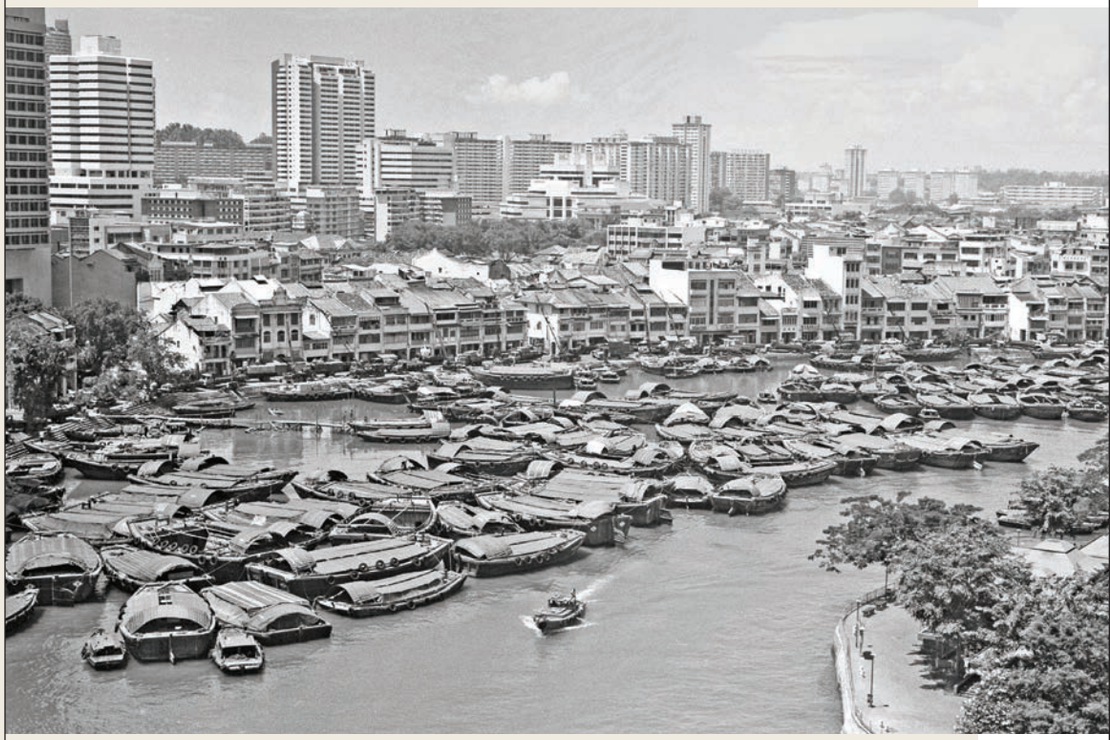
Since 2011, three new reservoirs in Marina, Punggol and Serangoon have been created, bringing the total number of reservoirs in Singapore to 17. With this, Singapore's water catchment area has increased to two-thirds of Singapore's landmass.[20]

CLEANING THE SINGAPORE RIVER—PROVIDING ALTERNATIVES, MANAGING TRADE-OFFS

The master plan for cleaning up the Singapore River and Kallang Basin was drawn up in October 1977. Apart from the PUB, the river clean-up taskforce also involved the MND, MTI, Ministry of Communications and Information, Ministry of Law, and agencies such as the HDB, URA, JTC, Public Works Department (PWD), Primary Production Department (PPD), Port of Singapore Authority, and Parks and Recreation Department (PRD). Beyond the technical aspects of the clean-up, the plan also focused on changing the people's way of life in order to reduce the sources of pollution.

Approximately 46,000 squatters around the catchment areas had to be resettled. All Singaporeans or business establishments affected were offered re-housing and compensation while non-Singaporeans were allowed to rent flats. Close to 5,000 street hawkers were relocated to markets and hawker centres in Boat Quay, Empress Place and Chinatown. Vegetable wholesalers were relocated to the Pasir Panjang Wholesale Market. Members of Parliament (MPs) helped address many requests and sometimes unusual grievances from the resettled squatters, for instance, one complaint was about how joss sticks were burning faster at the higher floors of their new flats. However, there were no major protests against the resettlement.

The highly-pollutive pig farms were phased out in 1984. The PPD had wanted to protect the pig farming industry as a strategic food supply in times of war but the case for pig farming collapsed when Second Deputy PM Dr Goh Keng Swee learnt that the feedstock for the pigs was imported; he asked, "If you can import the feedstock—why not import the pork?"[21] The removal of pig farms was difficult as many farmers were unable to adapt to apartment life. The newspapers reported that one farmer hanged himself.[22] PM Lee Kuan Yew recalled that the farmers felt the government had destroyed their way of life and many voted against the People Action Party (PAP) for many years afterwards.[23]



The Singapore River before its clean-up.
Image from the Ministry of Information and the Arts Collection, courtesy of the National Archives of Singapore.

CLEANING THE SINGAPORE RIVER—PROVIDING ALTERNATIVES, MANAGING TRADE-OFFS

Continued...

All bumboats were relocated to the cargo handling storage and mooring facilities at Pasir Panjang. As the bumboat operators had complained about stronger waves at Pasir Panjang and the distance they would have to travel back to Chinatown to have lunch at home, the government constructed a breakwater and set up a canteen at Pasir Panjang. Concerns that this move would have an impact on Singapore's entrepôt trade proved unfounded. The larger boatyards in the Kallang Basin were required to upgrade their operations to comply with anti-pollution requirements. Small boatyards that could not upgrade their operations were offered alternative sites in Jurong. However, the shipyards that had been adding to pollution in the Tanjong Rhu river due to ship painting, scraping, and oil, grease and other types of discharge from unsewered workers' dormitories were not moved. The EDB had been against relocating these shipyards as they were generating revenues of S$60 million a year.

Hawker stalls along the Singapore River in 1970.
Image from the A.J. Hawker Collection, courtesy of the National Archives of Singapore.

View of South Boat Quay in 1987 after the Singapore River clean-up.
Image from the Ronni Pinsler Collection, courtesy of the National Archives of Singapore.

Besides addressing the primary pollution sources, more than 260 tonnes of existing rubbish in the rivers and river banks were collected and disposed during a month-long operation. In 1986, the PWD also tiled the walkway along the Singapore River, while the PRD carried out landscaping work along the banks. The Kallang Basin riverbed was dredged to remove the mud at the bottom and one metre of sand was put in. To prevent further pollution, the government put in place drain covers in litter prone areas, vertical gratings at outlet drains, and float booms at rivers and canals to trap inorganic litter.

The clean-up was completed in 1987 and cost the government nearly S$300 million, excluding resettlement compensation. Apart from boosting Singapore's water supply, it also served a visible symbol of what was to be a larger clean-up in Singapore.

The Second National Tap—Imported Water

For many years, the adequacy of Singapore's water supply was contingent on Singapore's two water agreements with Malaysia. What Singapore would do after the expiry of the Water Agreements in 2011 and 2061, respectively, was a question that needed to be addressed seriously. However, alternatives such as desalination were thought to be far too costly to be seriously considered.

However, in the aftermath of the Asian financial crisis of 1997–1998, rising tensions between Singapore and Malaysia precipitated a series of increasingly acrimonious discussions centred on extending the Water Agreements. As Malaysia faced the threat of water rationing in early 2000, some Malaysians felt that water from Johor should first fulfil Malaysian, rather than Singaporean, needs. When tensions mounted, Malaysia's PM Mahathir Mohammed led a rally in Johor in 1998, where thousands of United Malay National Organisation (UMNO) members chanted, "*Potong*! *Potong*!"—an implied threat to cut ("*potong*") Singapore's water supply. PM Lee recalled PM Mahathir saying that Singapore had been undercharged for the water and the Malaysians threatened to raise the price from RM0.03 to RM8. "We were under serious blackmail," PM Lee recalled.[24]

Given the situation then, the PUB intensified its efforts to establish additional National Taps, in the forms of recycled water and desalinated water to diversify Singapore's water supply. Nevertheless, imported water from Malaysia remains a critical component of Singapore's water supply, and Singapore continues to draw 250 mgd of water from the Johor River under the 1962 Water Agreement.

The Third National Tap—Introducing NEWater

The PUB had experimented with treating and reclaiming water in 1974. In October that year, Singapore's first pilot water reclamation plant, a joint project by the PUB and the ENV, was commissioned at the Jurong Industrial Waterworks. Project advisor Tan Teng Huat of the PUB's Water Reclamation Department had drunk a glass of reclaimed water in

January 1975 and declared that the water was "not bad at all". However, the plant encountered problems such as a strong smell of ammonia in the water and was shut down in late 1975 after the test period. This shutdown was not made known to the public—there were no plans to continue with water reclamation as doubts remained about the reliability of the technology. However, over the next 20 years, the PUB continued to keep abreast of the development of the technology.[25]

> *We would have proceeded with NEWater irrespective of all these political developments. These political developments only added a sense of urgency to the issue.*[26]

In the 1990s, technological advancements in water reclamation enabled more manufacturers to produce good quality membranes. The cost of membranes fell by 50%, and with that, reverse osmosis and microfiltration became economical. The President of Dow Corning assured PM Lee when they met for a discussion in the late 1990s that membrane technology would improve and become less expensive, and "[would] solve his problems".[27]

In 1998, Lee Ek Tieng, by then Chairman of the PUB, and Tan Gee Paw, then-Permanent Secretary for the ENV, started to revisit the idea of recycling water. Two engineers from the PUB, Harry Seah and Goh Cheng Woon were sent on a two-week study trip to see how water was recycled in the United States (US). They visited cities in Southern California and Florida to study a full range of water recycling methods, from the conventional to the part-conventional, and the use of membrane technology. The trip was pivotal in Singapore's efforts to recycle its water. As Seah put it simply, "Seeing is believing."[28] Just two days following the assessment by Seah and Goh that water reclamation was feasible, Lee and Tan committed to the construction of a demonstration water reclamation plant of 2.2 mgd at Bedok to determine the feasibility of using reclaimed water as an additional source of water. The plant started its operations in May 2000. Tan took on the role of Chairman of the Steering Committee for the project. (See Appendix 3 for details on the production process of NEWater.)

Two years of intensive trials followed, where more than 20,000 tests on 150 water quality parameters were carried out on the reclaimed water. The Steering Committee also conducted a comprehensive study to ensure that the reclaimed water was well within the World Health Organisation's Drinking Water Guidelines and the United States Environmental Protection Agency's Drinking Water Standards, and that there were no long-term health risks. An independent panel of experts comprising both local and foreign experts was set up to ascertain the usability of NEWater. This panel included some of the experts the PUB team had met in the US. The expert panel also verified that the water was suitable as raw reservoir water for Indirect Potable Use (IPU) in accordance with international practice.

The PUB team had seen from its trip to the US that it would be tough to overcome the psychological barrier the population would have in drinking recycled water. In the US, recycled water was injected into groundwater before being used for drinking, even though the quality of the recycled water was good enough for direct consumption. Across the world, very few countries had successfully used recycled potable water for drinking—the "yuck factor" would be no different in Singapore. Without public acceptance, NEWater would fail as an alternative source of water. Backed by the Cabinet, the PUB and the ENV began an extensive public education exercise in July 2002 that culminated in a high visibility event at the 2002 National Day Parade on 9 August 2002, where PM Goh Chok Tong led 60,000 people in a toast to Singapore with NEWater (see Box Story, page 24).

The PUB and the EDB also made efforts to encourage industries to use NEWater, in particular, seven wafer fabrication companies at Tampines/Pasir Ris and Woodlands. The PUB absorbed the costs of connecting pipelines from the mains to the meter and the necessary retrofitting works from the meter to the tanks, as well as for the certification and corrosion studies by their specialists. The PUB also built a separate pipeline for NEWater and assured the companies that the plants and distribution pipelines were designed with sufficient backup capabilities. Once the industry accepted NEWater as a high-quality substitute for potable water, its demand increased. The main industrial consumers were wafer fabrication plants, refineries and petrochemical companies. Others included power stations, electronics companies and commercial premises.

As of 2019, Singapore has five NEWater plants.

The Fourth National Tap—Desalinated Water

In 2005, the PUB developed the fourth National Tap—desalinated water. In 1995, a team consisting of officials from the PUB, URA, Ministry of Trade and Industry (MTI) and the National Science and Technology Board visited Saudi Arabia, the United Arab Emirates and Malta to learn about desalination technology and management. In 1999, the Cabinet approved the building of Singapore's first desalination plant. In 2003, the PUB awarded a Design-Build-Own-Operate (DBOO) contract for this desalination plant, named the SingSpring Desalination Plant (SSDP). This became one of the PUB's pioneer public-private partnership projects.

At the grand opening of SSDP in 2005, PM Lee Hsien Loong "turned on" Singapore's fourth National Tap. To enhance Singapore's resilience to drought, the PUB built another two desalination plants in 2013 and 2018. By 2020, two additional desalination plants will be completed, one at Marina East and the other on Jurong Island.

GETTING PAST NEWATER'S "YUCK FACTOR"— BRINGING THE PUBLIC ON BOARD

The NEWater Steering Committee had studied how other countries had tried to get their citizens to accept reclaimed water as potable water and discovered that their emotive response to used water and its association with sewers and toilets was a large reason why such attempts failed.

The first challenge was to find a name for the product. A descriptive name like "Recycled Water" was clearly not going to work. Lee Ek Tieng, the committee chairman recalled that the committee wanted a fresh name for the product and that was how the term "NEWater" came about, by combining the words "New" and "Water".[29]

But just having an acceptable name was not enough. The PUB and the ENV took the lead in a public awareness campaign, which was supported by a panel of experts. Singapore-based reporters were brought to the US and the UK where they saw how recycled water had been used for drinking. Initially, the plan was to have international water experts "sell" the NEWater plan to Singaporeans. However, the government soon realised that an approach that was too technical would not work and decided that officials from the relevant government agencies, along with the Ministers and MPs, would have to front the public education exercise.

NEWater bottles are easily identifiable by their bright and colourful labels.
Image from the Ministry of Information, Communications and the Arts Collection, courtesy of the National Archives of Singapore.

Prime Minister Goh Chok Tong drinking and endorsing NEWater after a game of tennis at the Istana in 2002.
Image from the Ministry of Information, Communications and the Arts Collection, courtesy of the National Archives of Singapore.

GETTING PAST NEWATER'S "YUCK FACTOR"—BRINGING THE PUBLIC ON BOARD

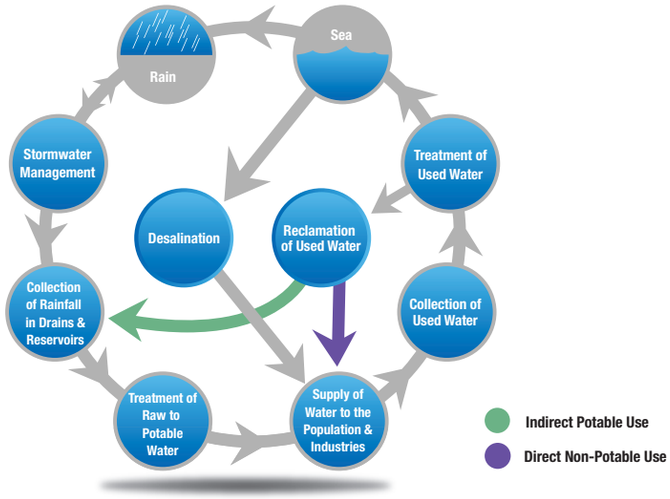
Continued...

Many grassroots leaders and politicians were invited to the NEWater demonstration plant in Bedok, where the discharge chamber had been intentionally painted white to showcase the purity of NEWater. This chamber was nicknamed "the Jacuzzi"—the pristine blue water inside the chamber with its clear froth bubbling against the background made for a strong visual selling point. In addition, former Minister for the Environment Lim Swee Say brought groups of 3 to 4 hundred community leaders to the plant and explained the NEWater process to them. The NEWater team felt that they had a good shot at winning the battle against the "yuck" factor when the MPs and grassroots leaders, who were encountering NEWater for the first time, got excited over how clear, odourless and clean the water was.[30]

After winning over the media and community leaders, the PUB worked to engage and educate the public. It pointed out that the US had been reclaiming water for drinking for more than two decades with no long-term health concerns surfacing. In addition, the quality of NEWater in many cases exceeded that of drinking water in other countries. (In fact, Lee liked to tell sceptical friends that the purity of NEWater made it ideal for mixing with whiskey.) The PUB produced bottled NEWater for the public to try at national events and a NEWater Visitor Centre was set up. During the 2002 National Day Parade, 60,000 participants joined PM Goh in a NEWater toast to Singapore. Public education on NEWater continued into 2003 through the mainstream media and schools. In February 2003, PM Goh officially opened the NEWater Visitor Centre.

The NEWater Visitor Centre offers interactive exhibits and viewings of the water purification facility.
Image courtesy of PUB, Singapore's National Water Agency.

THE WATER LOOP



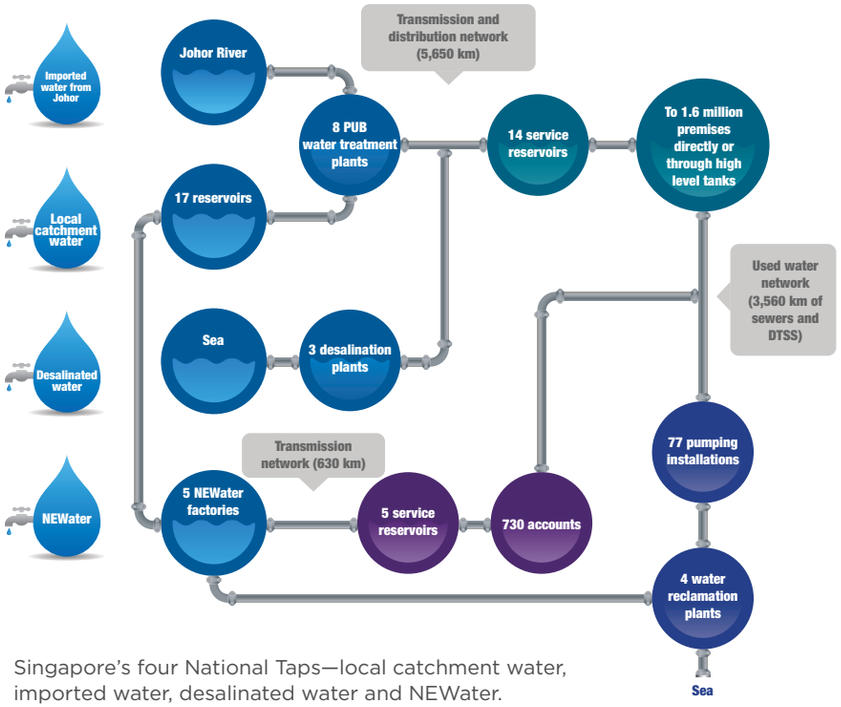
The water loop concept.
Image courtesy of PUB, Singapore's National Water Agency.

The three National Taps that draw from domestic sources form part of a closed "water loop" that is the basis for sustainable water supply. The water loop works with the limitations and opportunities of Singapore's situation—limited land, little groundwater, a colonial legacy of separate systems of sewerage and drainage, abundant rainfall and even more abundant seawater. The fundamental principles behind this concept are: capture every drop of rainwater, collect every drop of used water, and reuse every drop of water more than once. The closed water loop system mirrors a closed feedback loop and the act of water recycling creates a multiplier effect, allowing for the yield of the existing water supply to increase exponentially with increased recycling of used water.

Conceiving the water loop required a good dose of imaginative thinking on the part of water agency officials to complement engineering expertise. NEWater, for instance, was a significant water system innovation for Singapore, both in terms of engineering and how the country viewed its water supply. Likewise the move to make use of every drain and canal possible to collect rainwater, as well as the intensive expansion of the reservoirs network—including the building of functioning reservoirs in urban areas—came from an unusual philosophy that advocates that more

than 60% of Singapore's land area could and should be turned into water catchments. Indeed, the country's aim is to have 90% of its land area as water catchments by 2060.

With an eye on ensuring a well-integrated water management system, the PUB was transferred out of the MTI in 2001 and merged with the Sewerage and Drainage Departments of the ENV. It also divested its functions concerning energy to be exclusively focused on water issues. With the integration of the drainage and sewerage functions under the PUB, it now became the national water agency in charge of all operational nodes in the entire water loop—from rainwater collection to the purification and supply of drinking water, to the treatment of used water and its reclamation into NEWater, Singapore's own brand of high-grade reclaimed water. The production of desalinated water became part of the water loop in 2005. This was an essential move that allowed Singapore's water, sewerage and drainage systems to be managed in an integrated and holistic manner.



Singapore's four National Taps—local catchment water, imported water, desalinated water and NEWater.
Image courtesy of PUB, Singapore's National Water Agency.

Reservoirs

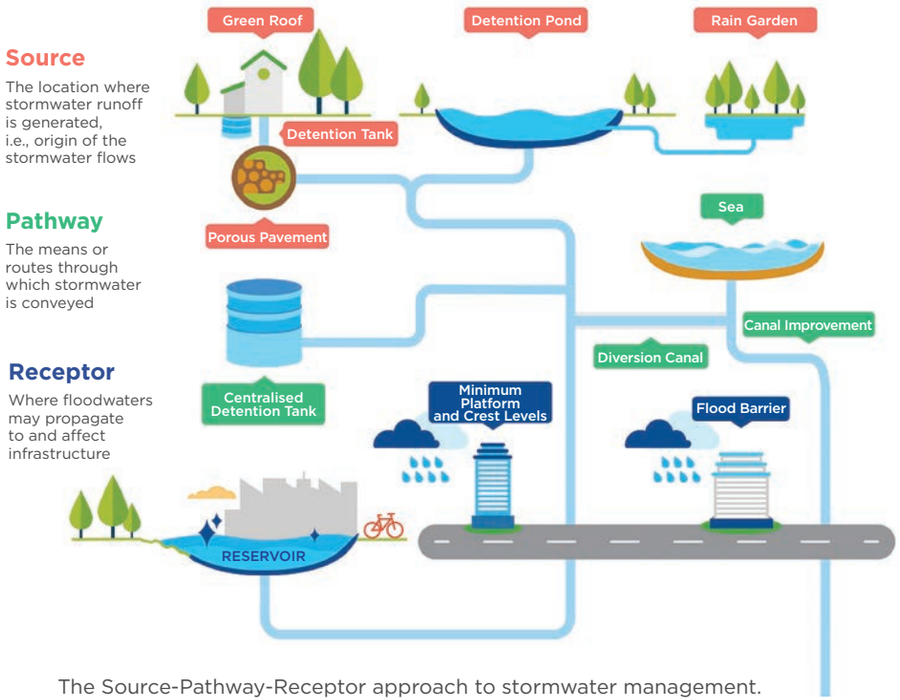
The Reservoir Integration Scheme (RIS) that started in 2004 connected the various reservoirs by a system of pumps and pipelines, which enabled excess water in one reservoir to be pumped to another for storage. This was necessary as the catchments and reservoirs were of different sizes. For instance, a reservoir like Kranji has a smaller storage capacity relative to the size of its catchment, leading to frequent overflows and wastage. Dams were built across Sungei Punggol and Sungei Serangoon, creating 5,000 ha of new catchment in north-east Singapore. The RIS was completed in 2007 at a cost of S$18 million.

Drainage System

Along with the Land Transport Authority, the PUB and the NEA formed the Road Drainage Improvement Task Force to rectify flooding and "ponding" problems on the roads. Singapore has invested more than S$2 billion in its drainage infrastructure since 1973. The size of flood-prone areas in the country has been drastically reduced from 3,200 ha in the 1970s to just 29 ha in 2019.[31]

In 2005, the government embarked on its most ambitious drainage project—building the Marina Barrage. The Marina Basin sat prominently in the southern part of Singapore. The Barrage had started as a drainage project but eventually evolved into a functioning urban water catchment as well (see Box Story, page 34).

Despite all the improvements to the infrastructure, the floods that struck parts of Singapore in 2010 and 2011, particularly in Orchard Road and Bukit Timah, were a reminder that Singapore's best engineering systems can still be bettered by Mother Nature. While building higher capacity drains may seem the logical solution to reduce flooding, this is not sustainable in the long run in view of competing land uses, weather uncertainties and the possible impact of climate change. The PUB is looking towards more adaptable, flexible and sustainable measures to achieve higher drainage and flood protection standards for Singapore. To this end, the PUB has adopted a multi-pronged approach that covers the entire drainage system, from "source" (where stormwater runoff is generated), to "pathway" (drains and canals through which stormwater is conveyed), and then to "receptor" (where floodwaters may flow to and affect infrastructure).



The Source-Pathway-Receptor approach to stormwater management.
Image courtesy of PUB, Singapore's National Water Agency.

In the past, the conventional approach was to convey stormwater away into the sea as quickly as possible. In recent years, the PUB started working with stakeholders to build more flexibility into the drainage system. Starting from 2014, the PUB requires developers of all new developments and redevelopments that are 0.2 ha or more in size to implement "source" measures to slow down surface runoff from flowing into the downstream drains and canals.[32] Such measures include installing detention tanks, retention ponds, green roofs and rain gardens.

"Pathways" can be improved by increasing the drainage capacity of existing canals and building new canals or diversion canals, or centralised detention systems. In 2011, the PUB raised the design standards of drains to increase the level of flood protection.[33] Depending on its size, each catchment will have its drainage system upgraded in capacities between 15 and 50%.[34]

To protect infrastructures from flash floods, the PUB amended the Code of Practice on Surface Water Drainage in 2013 to raise the development standards for "receptors", such as minimum land reclamation levels as well as platform and crest levels.[35]

The PUB also undertook drainage improvement works at a total of 359 locations between 2012 and 2018.[36] These included the Stamford Detention Canal (SDC), Stamford Detention Tank (SDT) and Bukit Timah First Diversion Canal (BTFDC), which helped to alleviate floods in the Orchard Road and Bukit Timah areas, respectively. The SDC diverts water from the upstream section of the Stamford Canal catchment towards the Singapore River.[37] The SDT, an underground detention tank with a storage capacity of 15 Olympic-sized swimming pools, was constructed near the junction of Tyersall Avenue and Tyersall Road.[38] The tank captures excess stormwater from the drains along Holland Road during heavy rainfall and pumps it back for discharge into Marina Reservoir once the rain subsides.[39] The expansion of the BTFDC—which involved deepening and widening the canal along Bukit Timah Road—and construction of additional tunnels were completed in 2019 at an estimated cost of S$300 million.[40]

In 2018, Prime Minister Lee Hsien Loong visited the Stamford Detention Tank, which is located beneath the Singapore Botanic Gardens.
Image courtesy of the Ministry of Communications and Information.

Sewers

Singapore is 100% served by modern sanitation today. Used water from households, industries and commercial premises is collected and transported via a 3,560 km network of sewers to water reclamation plants for treatment. The PUB adopts a preventive approach of enhancing the reliability of the sewerage system through an on-going rehabilitation programme. Currently in Phase 5 (2017–2024), the programme will rehabilitate ageing sewers that are more than 40 years old, while sewers that are between 20 and 40 years of age will be rehabilitated based on condition assessments through inspections.[41]

The award-winning Deep Tunnel Sewerage System (DTSS) was conceptualised in the mid-1990s as a long-term solution to collect and treat used water from homes and industries, before discharging it into the sea. The tunnel system runs for 48 km and is 20 to 55 m below ground (sewerage pipes are generally 5 to 6 metres deep). It makes use of gravity to convey the used water, thus eliminating the need for intermediate pumping stations and freeing up 110 ha of land for other uses upon the completion of DTSS Phase 1. The depth of the tunnels also reduces the risk of surface water pollution (see Appendix 4 for more details on the DTSS). Phase 1 was completed in 2008 and it channelled water to the Changi Water Reclamation Plant (CWRP) for treatment. The treated water was then used by the NEWater factory situated at the rooftop of the CWRP. Construction of the DTSS Phase 2 started in 2017 and will be completed in 2025. Similar to the Phase 1's CWRP, the new Tuas WRP will also be integrated with a NEWater factory. Phase 2 extends the existing DTSS to collect used water from the western and southern parts of Singapore. When completed, Phase 2 will have a conveyance system made up of 60 km of link sewers and 40 km of deep tunnels. It would also have phased out existing intermediate pumping stations and water reclamation plants.[42]

Technology has enabled Singapore to "close" the water loop into a largely self-sustaining water supply system, and the institutional changes to the PUB have allowed a more integrated approach to managing this loop. However, each node is not necessarily functioning at its most efficient. For instance, the PUB sees that there is still scope to reduce the energy used for desalination (3.5 kWh/m^3). Flash floods will continue to be a challenge in the face of climate change. As such, apart from investment in infrastructure, the PUB runs research and development (R&D) projects to improve and fine-tune the operations of each node of the water loop.

THE MARINA BARRAGE— MORE THAN JUST A DRAINAGE PROJECT

In a television interview in the late 1980s, shortly after the Singapore River clean-up, PM Lee offered his vision of what the Marina catchment could be like in 20 years. Assuming that there were breakthroughs in technology, a barrage could be established at the mouth of the Marina, creating a huge lake that would serve as a freshwater reserve for emergencies and as a mechanism for flood control. PM Lee raised the idea repeatedly, but each time it was rejected by Lee Ek Tieng due to the poor water quality at the Basin and inadequate technology.[43] But two decades later, membrane technology had been tested by NEWater and the Marina Barrage project finally looked feasible.

The Barrage was originally conceived as a drainage project to prevent flooding in the Central Area.

However, during the construction of the Barrage, the PUB decided to create a full-fledged reservoir for supplying water, not just a marginal source. Membrane technology had improved and the falling costs of operation and maintenance meant that raw water from highly urbanised catchments such as the Marina Catchment could be cost-effectively treated for potable use. The successful clean-up of the Singapore River more than a decade ago also helped make the Marina Reservoir feasible.

Marina Barrage, an attractive recreational destination for picnics and kite-flying.
Image courtesy of PUB, Singapore's National Water Agency.

Construction for the Marina Barrage began in 2005 and was completed in 2008. It was officially opened by PM Lee Hsien Loong on 31 October 2008. On 20 November 2010, Marina Reservoir, which has a catchment area one-sixth the size of Singapore, was commissioned as Singapore's 15th freshwater reservoir.

The Marina Barrage earned several international and local engineering awards and was featured in the Discovery Channel's much-watched Man-Made Marvels series in 2008.

THE MARINA BARRAGE— MORE THAN JUST A DRAINAGE PROJECT

Continued...

For the government, the Marina Barrage was more than just an engineering project. The Barrage was also conceived as a lifestyle attraction. Given its prominent location in the city, the URA persuaded the PUB to design an iconic barrage, rather than the typical "square ugly structure".[44] It was landscaped as a public area with food and beverage outlets, a water playground, an art trail, and a Sustainable Singapore Gallery. Visitors could watch the crest gates being lowered and see the water gush into the sea. As the Marina Basin is unaffected by the tides, its water level can be kept constant all year round, making it ideal for recreational activities such as boating, windsurfing, kayaking and dragon boating.

The Marina Reservoir and Marina Barrage.
Image courtesy of PUB, Singapore's National Water Agency.

CHAPTER 3

MANAGING DEMAND

> "Right from the beginning, the government wants to get the message across to the electorate that water is vital to Singapore's survival. And you have got to pay for it."

Lee Ek Tieng[45]

PRICING AND INCENTIVES—THE ECONOMICS OF WATER

Unlike many other countries, Singapore does not treat water as a public good and puts a price on water use. The government did not budge much on the principle of charging for water to, at the minimum, recover the cost of production. Even when it comes to convincing companies to set up in Singapore, the high prices for water have, by and large, remained to push the conservation message, and the government has to find alternate fiscal incentives to convince these companies.

From as early as the 1970s to the mid-1990s, the Singapore government has attempted to manage domestic water consumption through policy instruments such as the pricing system, incentive schemes and regulation.

Tiered Pricing. In the 1970s, as demand for water rose, the government increased water prices to promote conservation rather than raise revenue.[46] Tiered pricing was introduced in 1973 to discourage excessive household consumption and extended to the non-domestic sector eight years later. Throughout the early to mid-1980s, water prices increased three times in the face of tight supply.

Water Conservation Tax (WCT). Introduced in 1991 to discourage excessive consumption of water, a 5% WCT was levied on households that consumed more than 20 m^3 of water a month, while a 10% WCT was levied on all water used by non-domestic and shipping sectors.

Exhibit 1
Summary of Water Tariffs, 1972–1986

Category/Tranche	1972 (S$)	1973 (S$)	1975 (S$)	1981 (S$)	1983 (S$)	1986 (S$)
Domestic: ≤20 m^3	$0.22/m^3$	$0.22/m^3$	$0.30/m^3$	$0.35/m^3$	$0.42/m^3$	$0.53/m^3$
Domestic: >20–25 m^3				$0.45/m^3$	$0.57/m^3$	$0.75/m^3$
Domestic: >25–40 m^3		$0.26/m^3$	$0.40/m^3$			
Domestic: >40–50 m^3				$0.75/m^3$	$0.95/m^3$	$1.10/m^3$
Domestic: >50–75 m^3		$0.33/m^3$	$0.50/m^3$			
Domestic: >75 m^3		$0.44/m^3$	$0.66/m^3$			
Non-Domestic: ≤50,000 m^3	$0.44/m^3$	$0.44/m^3$	$0.66/m^3$	$0.75/m^3$	$0.95/m^3$	$1.10/m^3$
Non-Domestic: >50,000 m^3				$0.85/m^3$	$1.10/m^3$	
Shipping	$0.88/m^3$	$0.88/m^3$	$1.32/m^3$	$1.55/m^3$	$1.95/m^3$	$1.95/m^3$

Source: PUB, Singapore's National Water Agency.

Water-saving Devices. Since 1983, water-saving devices such as constant flow regulators and self-closing delayed action taps were made mandatory in all non-domestic premises. Low capacity flushing cisterns were installed in all public housing apartments in 1992 and made mandatory for all housing projects since 1997.

Water Conservation Incentives. With the non-domestic sector accounting for 55% of water use,[47] PUB, Singapore's National Water Agency, and the Economic Development Board put in place fiscal incentives for companies to invest in water conservation facilities.

Despite the measures, both total and per capita consumption continued to increase. A pricing review in 1997 concluded that water should be priced to recover the full cost of production and supply through the water tariff and reflect the opportunity cost of supply by taking into account the cost of the "next drop" of water. Marginal cost pricing formed the crux of the reformed water pricing mechanism. In 1997, the "next drop" was benchmarked to water desalination.

The price of water was increased to S$1.52/m^3 and then to S$2.03/m^3 for domestic consumption above 40 m^3 per month in 2000. Of the S$1.52 price, the WCT accounted for S$0.35. Between 1997 and 2000, the tariffs for domestic and non-domestic consumption were also brought on par to prevent cross-subsidisation between the two sectors. Subsidies in the form of Utilities Save (U-Save) rebates were given to the lower-income groups.[48]

In 2018, the price of potable water was raised to S$1.82/m^3 for domestic consumption up to 40m^3 per month and non-domestic users, and S$2.51/m^3 for domestic consumption above 40 m^3 per month. This was to reinforce the message that water is precious, and reflect the cost of producing the next drop of water.[49]

NEWater, introduced in 2003, was priced to encourage industries such as wafer fabrication plants—which use significant amounts of water in their production processes—to switch to NEWater. However, it could not be priced too low as this would thwart the PUB's efforts to reduce water consumption. NEWater was eventually priced at S$1.30/m^3, based on cost recovery, in order to balance the two conflicting objectives.[50] It was initially exempted from the WCT and the tariff on NEWater was reduced to S$1.15/m^3 in 2005 and then S$1.00/m^3 in 2007 due to economies of scale in its production. However, with the economic downturn in 2008, projections of demand for NEWater fell. Investments have also been made in NEWater infrastructure projects. This led to an increase in the NEWater tariff from S$1.22/m^3 in 2012 to S$1.28/m^3 in 2018. To encourage water conservation, a 10% WCT was imposed on NEWater in 2017.[51]

REDUCING UNACCOUNTED FOR WATER

On the part of the PUB, it reduced Singapore's unaccounted for water (UFW) from 11% in the 1980s to about 5% after 1996. UFW is the difference between the amount of water produced and the total amount of water accounted for. It mainly consists of water lost through leaks and the under registration of meters. The figure for UFW can be as high as 30% in some countries.

Beginning in 1983, in a move to reduce UFW, the PUB began replacing unlined cast iron pipes with ductile iron. To identify and fix leaks, the PUB surveys the network twice a year using acoustic leak detection equipment. Major pipelines are installed with dedicated leak sensors for early leak detection. Good quality meters were also purchased and installed to ensure accurate readings. The PUB also works closely with the Housing & Development Board (HDB), as well as private property owners and developers on the maintenance of private water systems (i.e., the pipes and equipment from the water meter to the tap) and has published a guide on UFW management. Legislation on the illegal siphoning of water was also put in place under the Public Utilities Act with heavy financial penalties and/or jail terms for the guilty parties. Stiff penalties were imposed on those who damaged the water mains. Singapore now has one of the lowest figures for UFW in the world.

WATER CONSERVATION INITIATIVES

Singapore adopts a multi-pronged strategy towards water conservation. Apart from pricing water to reflect its scarcity value, the government has introduced various programmes and leveraged public education to encourage water conservation practices.

Public Education and Engagement

The government tries to encourage Singaporeans to save water and practise good conservation habits through a mix of call-to-action and awareness campaigns, as well as public engagement activities.

The Save Water Campaign of 1998.
Image from the Ministry of Information and the Arts Collection, courtesy of the National Archives of Singapore.

One of the earliest public education events was the "Water is Precious" exhibition held in 1972 that was launched by then-Minister for the Environment Lim Kim San. In the following year, the government encouraged Singaporeans to voluntarily place a quota on their water consumption with the aim of reducing average household consumption by 10 to 40% so that there would not be the need for another round of water rationing.[52] The Save Water Campaign was launched in 1995, following projections that Singapore would run out of water by 2001 given its water consumption growth rate of 6% per year.

The Singapore World Water Day is held each year in March with the theme "Make Every Drop Count". It serves as a platform to rally the community to celebrate and conserve water through a variety of community events such as "water rationing exercises" and roadshows. The former events are conducted in schools to allow students the experience of not having a water supply at tap points, as a means of getting them to cherish water as a precious resource.

An educational poster—"Let's Save the Precious Water"—in 1975.
Image courtesy of PUB, Singapore's National Water Agency.

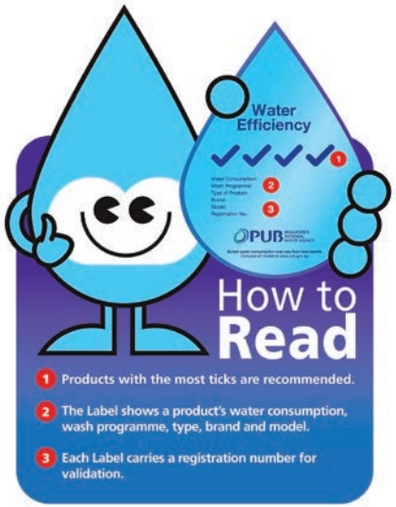
The PUB also works with the Ministry of Education to incorporate water topics in the school curriculum to inculcate good water-saving habits in children. For example, schoolchildren learn about various water topics such as the four National Taps, water conservation and the technologies used to produce safe and clean drinking water. They also learn about water sustainability in Singapore and how NEWater is produced through interactive tours and educational workshops at the NEWater Visitor Centre.

Reducing Household Water Consumption

The Mandatory Water Efficiency Labelling Scheme (MWELS) was introduced in 2009 to help consumers make more informed purchasing decisions and encourage suppliers to introduce more water-efficient products into the market. The scheme covers water fittings such as taps and mixers, dual-flush low capacity flushing cisterns (LCFCs), urinal flush valves and waterless urinals as well as washing machines. At the same time, to complement the MWELS, minimum water efficiency standards for water fittings were introduced. For instance, all new developments and existing premises undergoing renovation are required to install water fittings with at least a "1-tick" water efficiency rating. The PUB extended the MWELS to include dishwashers in 2018. To further push for the use of more efficient water fittings under the MWELS, the minimum efficiency standards for the sale, supply and installation of taps and mixers, LCFCs and urinal flush valves/waterless urinals were raised to "2-ticks" in 2019.

In 2018, the PUB launched the Water Closet Replacement Project for older HDB flats (built between 1987 to 1992) to help households on community assistance schemes replace their water closets, basins and kitchen taps with more water-efficient ones. These replacements, which were done at no cost to the owners, helped households reduce their monthly water usage by 10% on average.[53]

The PUB also carries out studies to gain a deeper understanding of households' water usage patterns and habits, as well as what motivates water-saving behaviours. With better understanding, the PUB is better able to design and implement water conservation outreach programmes in a more targeted and effective manner.



The Water Efficiency Labelling Scheme.
Image courtesy of PUB, Singapore's National Water Agency.

Leveraging Technology

The PUB has been studying the effectiveness of the use of smart technologies, such as smart water meters and smart showers, in encouraging water conservation behaviours.

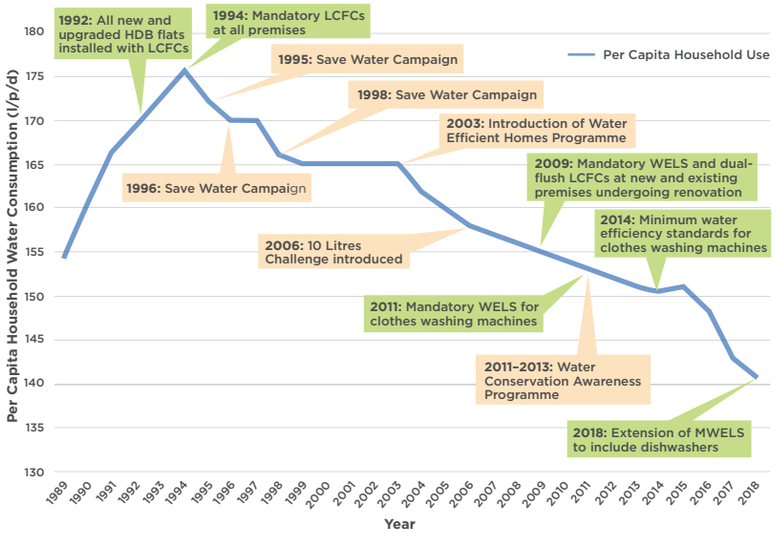
Pilot projects and trials of various Automated Meter Reading (AMR) technologies[a] have been carried out since 2011. More recently, the PUB embarked on a pilot project with SUEZ Environment to incorporate AMR in the Punggol and Yuhua estates in 2017 and 2018, respectively. As part of the study, consumers were presented with real-time information on their water consumption. They were also able to participate in gamification activities via a mobile app to challenge themselves to reduce their water consumption. Participating households in these estates were able to achieve a total average water savings of about 5%. As the trial has shown encouraging results, the PUB will be installing 300,000 smart water meters in new and existing residential, commercial and industrial premises by 2023, under the first phase of the Smart Water Meter Programme.[54]

In 2016, the PUB completed a randomised control trial (RCT) for about 500 households. In this RCT, real-time information on water consumption during showers was provided to the households through a smart shower device. The results from the field trial indicated that the households were able to save an average of 5 litres of water per person each day. Building on these positive findings, the PUB has deployed smart shower devices for 10,000 flats under a demonstration project with the HDB to further validate the water conservation effect of these devices.[55]

[a] Automated Meter Reading (AMR) involves the use of Smart Water meters to monitor and collect water consumption data. These meters enable consumers to understand their water usage and alert them to water leaks via a mobile app or online portal. The data collected will also be used by the PUB to optimise water demand management and achieve greater operational efficiencies.

Exhibit 2

Water Demand Management Strategies versus Daily Per Capita Domestic Water Consumption



Source: PUB, Singapore's National Water Agency.

Singapore's per capita consumption of water in households has been falling from 172 litres per day in 1995 to 141 litres in 2018. The PUB's target is to reduce Singapore's daily per capita consumption to 130 litres by 2030.[56]

Initiatives for Non-Domestic Sector

Non-domestic water demand currently forms 55% of the total water demand and this will continue to grow in the future. To address this, the PUB has devoted efforts to bring down water consumption in the non-domestic sector.

In 2008, the PUB launched the "10% Challenge" to encourage commercial and public buildings, hotels and schools to become water efficient and save 10% of their monthly water consumption. In June 2015, the PUB made it compulsory for large water users (of over 60,000 m^3 per year) to submit an annual Water Efficiency Management Plan (WEMP). This includes the requirement to measure and monitor their consumption through a private water meter. The PUB then studies the data collected from WEMPs to develop water efficiency benchmarks and publish best practice guides for various sectors (e.g., wafer fabrication, petrochemicals, etc.). Guides for other sectors will be published progressively.

Other initiatives to encourage non-domestic customers to reduce their water consumption include the Water Efficient Building (WEB) certification programme, Water Efficiency Manager Course and SS 577:2012, a national standard on water efficiency management systems.

The PUB is also working with the various industry sectors to promote the reclamation of used water as well as the use of seawater for cooling purposes, through three funding schemes—Water Efficiency Fund, Industrial Water Solutions Demonstration Fund and Living Lab—aimed at defraying the implementation cost of innovative technologies. To date, the PUB has facilitated the implementation of 22 projects through these schemes, resulting in savings of over 5 mgd of water.[57] Forums and seminars are also organised to facilitate the sharing of best practices and innovative technologies.

CHAPTER 4

BEYOND SURVIVAL MODE—WATER'S SOCIAL AND ECONOMIC ROLE

> "In the past, we protected our water resources by keeping people away from them; now we will bring people closer to water so that they will enjoy and cherish it more."

Lee Hsien Loong[58]

ACTIVE, BEAUTIFUL, CLEAN WATERS PROGRAMME

The Marina Barrage was created for practical reasons—drainage and water supply—but unlike previous water management projects, it placed emphasis on the project's aesthetic impact on the landscape and also factored in how the space could be used for recreational options. This was indicative of a new philosophy that was starting to emerge in PUB, Singapore's National Water Agency, to "bring the public closer to water".

The PUB started the Active, Beautiful, Clean Waters (ABC Waters) Programme in 2006 to transform the drains, canals and reservoirs beyond their utilitarian function into beautiful streams, rivers and lakes that could also be recreational sites. Khoo Teng Chye, Chief Executive of the PUB from 2003 to 2011, championed the ABC Waters Programme as he believed that ensuring the long-term sustainability of Singapore's water sources required the PUB to work in partnership with the public. If Singaporeans understood that the drains and canals were also water catchments, and if these prettied-up drains and canals made their environment more pleasant, they would be more likely to keep them clean. "It was [the] post-NEWater era and hence we could afford to explore improving the aesthetics of the drains, and there was tremendous political support," recalled Khoo.[59] (Note: there had been a precursor to the ABC Waters Programme. From 1989 to 2000, the Waterbodies

Design Panel assisted the Urban Redevelopment Authority in evaluating waterbodies linked to developments and to assess the aesthetic treatment of these developments along major waterbodies. Some of the projects included collaborations with the Ministry of the Environment's Drainage Department to transform the Sungei Api Api and Sungei Kallang drains.)

The PUB's long-term master plan for the ABC Waters Programme, launched in 2007, identified opportunities and potential projects across the island for the next 10 to 15 years. The PUB actively sought feedback from the community in developing the master plan. As part of the master plan, the PUB targets to implement this programme in more than 100 locations by 2030. To date, 43 ABC Waters projects have been completed.[60]

The ABC Waters Programme was inspired by the success of the National Parks Board's (NParks) Park Connector Network[61] and is aimed at transforming Singapore into a city of gardens and water by integrating its waterbodies with its parks and green spaces.[62]

The first ABC Waters demonstration project, "Kolam Ayer ABC Waterfront", was a partnership project between the PUB and NParks. It was officially opened to the public in April 2008. Demonstration projects at popular waterbodies such as Bedok and MacRitchie reservoirs were also rolled out.

In 2012, the flagship ABC Waters project—the Kallang River at the Bishan-Ang Mo Kio Park—was completed and launched. Also a collaboration between the PUB and NParks, the original concrete canal was naturalised into a meandering river and integrated within the Park. The river banks' gentle slopes and narrow stream in the middle provided recreational spaces for the community. In the event of heavy rainfall, the parkland adjacent to the river becomes part of the river to meet water conveyance functions. Soil bioengineering techniques were used to create stable river banks. The edges of the bio-engineered river form natural habitats, allowing urban biodiversity such as otters, damselflies and birds to flourish. The transformation has thus given rise to a blue-green recreational site integrated with residential housing.

Before and after photos of the Kallang River being naturalised at the Bishan-Ang Mo Kio Park.
Images courtesy of Ramboll Studio Dreiseitl Pte Ltd.

With the support of the Housing & Development Board, NParks and the Land Transport Authority, the PUB implemented pilot ABC Waters projects at waterways along roads and in parks and residential areas, to demonstrate that the ABC Waters design features were feasible and made a positive contribution to the landscape.

In 2009, the PUB published the *ABC Waters Design Guidelines* to encourage the public and private sectors to adopt ABC Waters design features and integrate waterways within new land development projects. From 2010 to 2018, a total of 75 such projects have received the ABC Waters Certification.[63] The PUB also pushed for an "ABC Waters scoring component" in the Building and Construction Authority's Green Mark Schemes, which recognises government agencies and private developers that incorporate ABC Waters into their projects.

At the same time, the PUB has adopted a 3P (people, public and private sector) approach in its outreach efforts on ABC Waters. Community events were held at various completed ABC Waters projects to bring Singaporeans "closer to water". The PUB has also been successful at encouraging communities to take ownership of their waterways. A series of experiential learning trails created with 3P partners at various ABC Water sites allows the community to learn more about the ABC Waters design features and water management. Schools and community groups have also adopted these ABC Waters sites—they organise clean-up activities, conduct water and biodiversity studies, and encourage the community to enjoy these sites and related facilities in a responsible manner.[b]

BIRTH OF A WATER INDUSTRY

The PUB recognised the need to work closely with industry, academia and international partners to develop solutions to overcome Singapore's unique challenges. Since the beginning, the PUB has been working with industry partners on water infrastructural projects including our waterworks, water reclamation plants, pipes, sewers, drains and more significantly the Deep Tunnel Sewerage System (DTSS) Phase 1 (2000–2008), large-scale NEWater plants and desalination plants since 2003, and the Marina Reservoir and Marina Barrage, which were completed in 2008.

By the 2000s, Singapore has made substantial investments in research and development (R&D) for solutions to overcome the challenges of water scarcity, particularly in developing the two latest National Taps—NEWater and desalinated water. Through these experiences, the PUB saw the need to have a local and vibrant water industry to support the delivery of the entire water value chain and to tap on a wide spectrum of technologies and innovation for collaborations.

[b] For more details on the development of the ABC Waters Programme, please refer to the USS publication *Active, Beautiful, Clean Waters Programme: Water as an Environmental Asset.*

The PUB started its industry development efforts in 2003 with the objectives of building industry capability, developing technology, and establishing Singapore as a Global Hydrohub. In 2004, the PUB worked with the industry to set up the Singapore Water Association (SWA) as a local industry-driven body to grow the water industry, and to profile Singapore as a water technology hub. The WaterHub was also launched in 2004 as a platform for the PUB and the water industry to develop technology, learn and network. In 2018, the PUB launched the Singapore Water Exchange, a specialised development within the WaterHub that is meant to house companies covering the whole value-chain, including system integrators, accelerators, investors, market advisors and associations. The development offers virtual offices and co-working space with flexible lease conditions. This provides a conducive environment for synergistic collaborations, making it easier for companies to test-bed and work on commercialising their products.

Adopting a Whole-of-Government Approach to grow the Water Industry

The PUB's early partnerships with the industry and its industry development efforts had built a local water industry of about 50 companies. In 2006, the Singapore government through the National Research Foundation (NRF) identified water as a key economic growth area. The multi-agency Environment and Water Industry Programme Office (now known as the Water Industry Programme Office [WIPO]), led by the PUB, was set up to develop the water industry and promote R&D. The Programme Office tapped the technical expertise of the PUB, alongside a close partnership with local agencies such as the Economic Development Board and Enterprise Singapore (ESG) to support the industry engagement component. With total funding of S$470 million from 2006 to 2015, the number of jobs in the water industry doubled to 14,000 and the annual value-add of the water industry grew to over S$2.2 billion. By 2016, there were over 180 water companies and more than 20 water-related public and private R&D centres in Singapore.

The WIPO adopts an integrated Whole-of-Government approach to engage and grow the entire water ecosystem based on these three focus areas:

i. ***Cluster Development:*** *To anchor activities from international companies, groom local companies and create a conducive environment to support start-ups and entrepreneurs.*

Singapore's water ecosystem today comprises large and small, local and foreign companies that span the entire water value chain. Many of these water companies leverage the diversity of Singapore's water ecosystem, regional connectivity and strong talent base to conduct a variety of business and research activities. In addition, local companies such as Keppel and Sembcorp have grown into global players in the international water market. The WIPO also works with small and medium-sized enterprises (SMEs) and start-ups to develop their technological capabilities. Some examples include Century Water, an advanced water treatment/engineering SME and Ecosoftt, an SME specialising in decentralised water treatment solutions.

ii. ***Technology Development:*** *To build up the R&D and technology base for the water sector, and develop the necessary talent and manpower to meet the needs of the sector.*

The PUB takes an active approach in R&D to facilitate and accelerate technology development. Its R&D approach is driven by its three strategic goals of increasing water resources, improving quality and security, and reducing the cost of production. The PUB is guided by an R&D Roadmap, which helps determine how new ideas fit into the whole scheme of things (See Appendix 5 for the PUB's R&D focus on 11 Technology domains of interests). Through various funding initiatives, the PUB provides support for R&D projects throughout the value chain, from upstream research such as conceptualisation of ideas and the seeding of new technologies, to the demonstration and commercialisation of technologies. Between 2002 and 2018, the PUB has undertaken 613 R&D projects valued at S$453 million in collaborations with partners from 27 countries.[64] The PUB, as the operator of Singapore's water system, also provides test-bedding sites for high-potential technologies to be tested in a real-life environment. Underpinning these are efforts to groom talent through PhD scholarship programmes and visiting professorships so that international know-how in key areas can be transferred to Singapore.

iii. ***Internationalisation:*** *Strengthening linkages with international partners by organising overseas missions and engaging in extensive marketing and branding activities that help Singapore companies secure international projects and to position Singapore as a Global Hydrohub.*

The PUB works closely with ESG to export Singapore-based capabilities through trade missions and government-to-government business councils. It also supports Singapore-based companies in expanding into higher value Design-Build-Own-Operate (DBOO) and Build-Operate-Transfer (BOT) projects by helping them develop their overseas strategy and facilitating collaboration with suitable partners. The PUB also supports Singapore-based companies to internationalise by providing advisory services in areas that the private sector may lack competency in.

In 2008, the PUB initiated the Singapore International Water Week (SIWW) to be a global platform for sharing and co-creating innovative water solutions among government leaders and water professionals. The SIWW has since gained traction and has established itself as a premier water event. Participation at the SIWW has grown from 8,500 participants from 79 countries in 2008 to 24,000 participants from 115 countries/regions in 2018. SIWW 2018 saw projects, tenders, investments and secured MOUs amounting to S$23 billion worth in value.[65]

Statistics on the various Singapore International Water Weeks over the years.
Image courtesy of PUB, Singapore's National Water Agency.

Full house at SIWW 2018's Tuas Nexus Business Forum.
Image courtesy of PUB, Singapore's National Water Agency.

Growing the Water Industry from 2016 to 2020

As part of the Research, Innovation and Enterprise (RIE) 2020 Plan, the NRF has set aside an additional S$200 million to grow Singapore's water industry to an annual domestic value-added contribution of S$2.85 billion and create 15,000 jobs by 2020. As of 2018, the industry is well on track to meet these targets with S$2.5 billion in annual value-add and 14,400 jobs created. The number of water companies and research institutes have also further grown to 200 and 25, respectively.[66]

Water, energy, land and liveability research activities are part of the Urban Solutions and Sustainability (USS) domain, which takes an integrated approach in responding to our urban challenges, and provides holistic support of Singapore's future growth, liveability and resilience. USS agencies including the PUB collaborate with industry partners to create economic value and establish Singapore as an international hub for sustainable urban solutions.

The SIWW Water Expo@City Solutions Singapore (CSS) in 2018.
Image courtesy of PUB, Singapore's National Water Agency.

Building Partnerships Internationally

Apart from developing innovative solutions locally, initiating discussions internationally enables Singapore to stay abreast of the latest water technologies and innovative solutions available. Singapore pulls together expertise and advanced technologies through international collaborations such as membership in research alliances, innovation workshops, and MOUs with regulatory bodies, research institutes and industry partners. For instance, the PUB signed an MOU with the Philippines' Metropolitan Waterworks and Sewerage System in 2019 to collaborate in water management, technology exchange and capacity training.

CHAPTER 5

MOVING FORWARD— FROM 2020 TO 2060

> "The world is at a critical turning point. Dealing with the impact of climate change and fundamentally transforming the way we produce and consume has become more urgent than ever."

Masagos Zulkifli[67]

WATER CHALLENGES

As Singapore prepares itself for the future, two key water challenges stand out.

The first is climate change—a phenomenon that we are already beginning to see signs of. Extreme weather patterns with more intense rainfall and severe dry spells and droughts may become more frequent. While we already have basic drainage infrastructure in place to cope with flood risks, we will need further improvements to better deal with heavier and more extreme storms.

On the other hand, droughts will also pose a serious problem. Without careful and advanced planning for severe droughts, there could be unthinkable consequences on the lives of the entire population. And indeed, the most challenging issue about climate change is that we are now seeing the occurrence of extreme weather phenomena. Past data on dry spells and droughts may not be relevant in predicting the severity of future droughts. We cannot forecast the future but we can keep ahead of future needs. The key is to safeguard what we have and bring forward our plans by building ahead of demand so that we are prepared to take on essential projects in the face of an impending crisis.

Singapore's second key challenge is complacency. As we celebrate the water journey that we have been on for the past 50 years, we may also have inadvertently become a victim of our successes. The millennials of today have not been exposed to the harsh realities of the yesteryears where water pollution and scarcity were commonplace. For the older generation, such memories become faint with time. Even the best made plans will not be able to keep up with burgeoning demands and needs. As a nation, we must not lose this sense of urgency and our survival instincts, to continue this journey towards efficient water use and ensuring water sustainability for generations to come.

Other challenges include keeping up with technology, using less energy in water production, and improving the network infrastructure.

PUSHING THE BOUNDARIES THROUGH R&D AND DIGITAL SOLUTIONS

PUB, Singapore's National Water Agency, will continue to invest in research and development (R&D) and technology, and work with the private and public sectors to develop innovative solutions, with the overarching goals of increasing water resources, improving water quality, and reducing production costs.

To bring down the costs of desalination and ensure its long-term viability, the PUB is looking into other forms of technology to extract fresh water from seawater. With the aim of at least halving current energy consumption levels, the PUB has partnered Evoqua Water Technologies to experiment with electrodeionisation technology to desalinate seawater.

Other exciting R&D in this area is based on biomimicry—or mimicking the biological processes by which mangrove plants and euryhaline fish extract seawater using negligible amounts of energy—and biomimetics, where proteins that allow the passage of water but not salts are embedded on membranes.

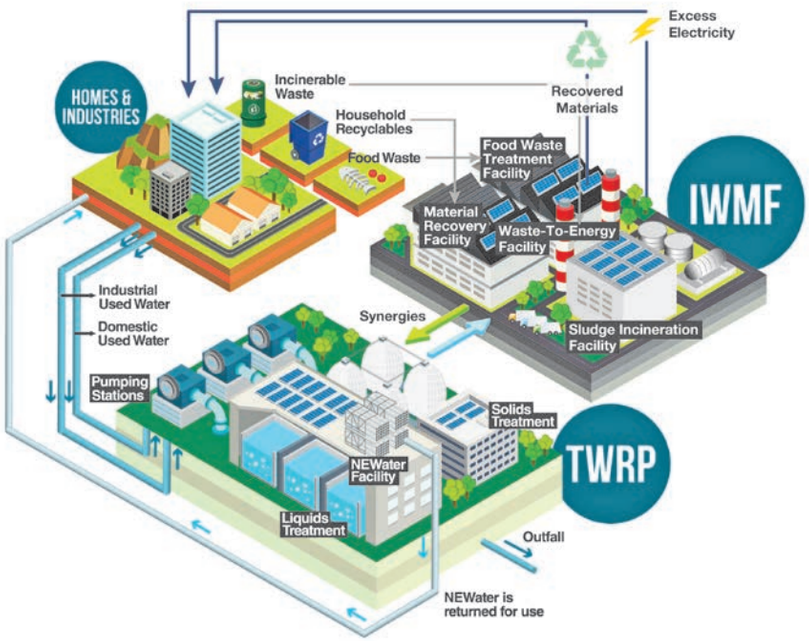


Diagram of the Tuas Nexus—co-location of the Integrated Waste Management Facility and the Tuas Water Reclamation Plant.
Image courtesy of the National Environment Agency.

The PUB and the National Environmental Agency have plans to co-locate the Deep Tunnel Sewerage System Phase 2's Tuas Water Reclamation Plant (WRP) with an Integrated Waste Management Facility (IWMF) to harness the potential synergies of used water and solid waste treatment processes. Collectively known to be Tuas Nexus, this new facility will be completed in 2025. In particular, sewage sludge from the Tuas WRP and food waste from the IWMF could be co-digested to generate additional biogas and therefore more electricity can be fed into the Tuas WRP for its operations. The Tuas WRP, in turn, can supply treated used water to the IWMF for cooling, hence allowing both plants to operate with higher efficiency. A two-year demonstration co-digestion plant at the Ulu Pandan WRP that was concluded in 2018 had proven that the co-digestion of food waste and used water sludge can increase biogas production by up to 40%,[68] which affirms the benefits of the Tuas Nexus.

The PUB has also been looking into underground water innovations such as the possibility of an Underground Drainage and Reservoir System, where the tunnels built can bring in excess stormwater into underground caverns for storage, with the aim of mitigating the impact of flood risks.

In 2018, the PUB unveiled a Smart Roadmap in a move to digitalise Singapore's entire water system and transform it into a smart water utility of the future. This involves the integration of smart technologies such as automation, robotics and artificial intelligence to boost operational excellence and efficiency. The PUB will also leverage pervasive sensing, data analytics and digital platforms to enhance system oversight, improve incident response, and ultimately strengthen service delivery to customers.

CAPABILITY DEVELOPMENT

In July 2016, the PUB launched the Singapore Water Academy and envisioned it to be a globally-recognised Academy for practitioner-focused training in urban water management. The Academy develops competency-based curricula to enhance the engineering competencies of PUB staff and offers specialised programmes for water professionals to prepare the industry for the next phase of growth.

A flagship programme of the Academy is its Singapore Water Management Series of four programmes—water quality management, water reuse, urban flood management and water supply networks—that will address the pressing needs of different cities. This programme combines international expertise with the PUB's practitioner-based experience, as well as draws on participants' unique experiences to have in-depth discussions on leading solutions currently available globally.

LONG-TERM SUSTAINABILITY

In June 2016, the PUB published Singapore's long-term water supply plan for the next 50 years. By 2060, Singapore's water use is expected to almost double from the current demand of about 430 million gallons a day, with water demand from industries forming the majority of our water demand. We will continue to enhance our water supply by increasing our water recycling and desalination capacity. By 2020, we would have built two more desalination plants at Jurong Island and Marina East; the Tuas WRP, which includes a NEWater factory, will be completed by 2025.

POST-SCRIPT

Enlightened water husbandry is the one thing that makes everyday life in Singapore possible, and our success and prosperity a continuing reality. Water has, is, and will always be, a national preoccupation. Safeguarding water security looms large in the minds of Singapore's leaders and the calculations of Singaporean administrators.

When it comes to water, Singapore's central challenge is overcoming scarcity.

Although right on the equator and smack in the tropics, Mother Nature has not endowed Singapore with quite enough water to get by. The constraints imposed by small physical size mean that there is just not enough space in Singapore to capture and to store all of the rainwater that we need.

We are in good company though. Big cities are invariably compelled to bring water from without to quench the thirst of their citizens within. Hong Kong, London, New York and Tokyo, just to name a few, all draw much if not the entirety of their supplies from large forest watersheds and rivers well outside of city limits. The 1962 Water Agreement, enshrined in the Separation Agreement that formalised Singapore's independence, guarantees us the right to abstract 250 million imperial gallons of raw water a day from the Johor River in neighbouring Malaysia. This imported water is an important source and can easily satisfy half of Singapore's current 430 mgd daily demand.

We have passed the halfway mark of this water agreement with Malaysia. It has 42 years more to run, and will expire in 2061. Come 2061, Singapore will of course consume a lot more water compared to what we are using today. PUB's estimate for daily water demand in 2061 is that it would, more or less, be doubled of what it is today. Where will all this additional water come from? Certainly not from our northern neighbour, as the water agreement would have come to an end. And not from the sky, as climate change would bring less rain. Anyhow, there is not much more space in Singapore for us to catch and keep more rainwater.

This additional water can only come from recycled water, and from the sea. We really have little choice. Hence, Singapore's water future lies with reuse and desalination. And so Singapore has to be the best in the world in these two areas. PUB has to lead the world when it comes to reclaiming used water and desalinating seawater.

Because we cannot afford to be caught without enough water, or have sewage overflowing onto our streets, or floods devastating the country, Singapore takes an uncommonly long view when it comes to water management, planning decades ahead. PUB water planners know that Singapore's water system must be adequate, resilient and sustainable, all at once.

Despite severely limiting geographical constraints, Singapore is not in water crisis. This is possible only because we as a country have been coldly realistic about our circumstances; because we have used our intellect and imagination, researching and testing continuously; and because we continue to muster the will to pursue and implement hard-nosed water policies.

Singapore believes that as long as we remain smart and clear-eyed about our country's water situation, and execute our plans relentlessly, there should always be enough water. In this remarkable way, when it comes to water, Singapore continuously seeks to turn disadvantage into strength, and seemingly unsurmountable vulnerability into endless opportunity.

Ng Joo Hee
Chief Executive
PUB, Singapore's National Water Agency

TIMELINE: KEY WATER MILESTONES

1961
- Signing of the First Water Agreement with Malaysia to give Singapore the exclusive rights to abstract water from the Gunung Pulai and Pontian catchments, and the Tebrau and Skudai rivers until 2011.

1962
- Signing of the Second Water Agreement with Malaysia, which allows Singapore to draw up to 250 million gallons a day from the Johor River until 2061.

1963
- Formation of the Public Utilities Board (PUB) as a statutory board under the Ministry of Trade and Industry (MTI).

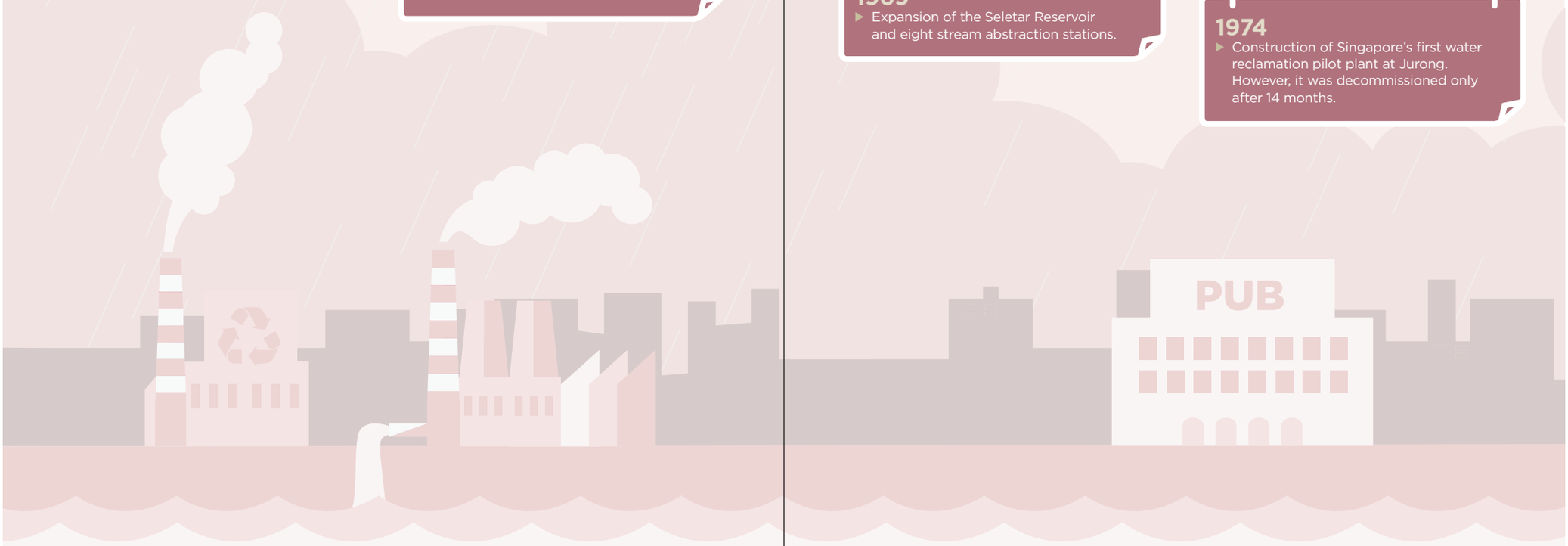
1966
- Introduction of industrial water with the construction of the Jurong Industrial Waterworks.

1969
- Expansion of the Seletar Reservoir and eight stream abstraction stations.

1971
- Launch of Singapore's first "Water is Precious" campaign.

1971
- Formation of the Ministry of the Environment (ENV).
- Introduction of Singapore's first Water Master Plan.
- Completion of the Bukit Timah Flood Alleviation Scheme Phase 1.

1974
- Construction of Singapore's first water reclamation pilot plant at Jurong. However, it was decommissioned only after 14 months.



1960s

1970s

1975
- Passing of the Water Pollution Control and Drainage Act.
- Completion of Singapore's first estuarine reservoir under the Kranji/Pandan Scheme.
- Completion of the Upper Peirce Reservoir and Chestnut Avenue Waterworks.

1977
- Relocation of pig farms.
- Launch of the Singapore River clean-up.
- Introduction of the Trade Effluent Regulations.

1979
- Commissioning of the Bedok Water Reclamation Plant (WRP).

1980
- Commissioning of the Kranji WRP.

1981
- Commissioning of the Seletar and Jurong WRPs.
- Completion of the Western Catchment Scheme (Sarimbun, Murai, Tengeh and Poyan reservoirs) and expansion of the Choa Chu Kang Waterworks.
- Introduction of Singapore's First Water Conservation Plan.

1983
- Introduction of the Water Catchment Policy, which aims to control developments within unprotected catchments.

1980s

1984
- Establishment of the Inter-agency Road Drainage Improvement Task Force.

1986
- Phasing out of pig farms.
- Completion of the Sungei Seletar/Bedok Scheme and the Bedok Waterworks.

1987
- Completion of the Singapore River clean-up.

1990
- Completion of the Bukit Timah Flood Alleviation Scheme Phase 2.

1991
- Introduction of the Water Conservation Tax.

1996
- Commencement of the Sewer Rehabilitation Programme Phase 1.

1997
- Restructuring of Water Pricing.
- Singapore is 100% served by a modern sanitation system.

1999
- Lifting of the 1983 Water Catchment Policy's urbanisation cap and population density limit.
- Commencement of the NEWater Study.
- Commencement of the Deep Tunnel Sewerage System (DTSS) Phase 1.
- Water Pollution Control and Drainage Act repealed and relevant powers streamlined into the Sewerage and Drainage Act and Environmental Pollution Control Act.

1990s

2000
- Commissioning of the NEWater demonstration plant at Bedok.

2001
- Reconstitution of the PUB to become PUB, Singapore's National Water Agency, and its transfer from the MTI to the ENV.
- Commencement of the Sewer Rehabilitation Programme Phase 2.

2003
- Public launch of NEWater by Prime Minister Goh Chok Tong.
- Commencement of operations at the NEWater factories at Bedok and Kranji.

2004
- Renaming of the ENV as the Ministry of the Environment and Water Resources (MEWR).
- Commencement of operations of Singapore's third NEWater factory at Seletar.
- Opening up of reservoirs for recreational activities.
- Formation of the WaterHub.

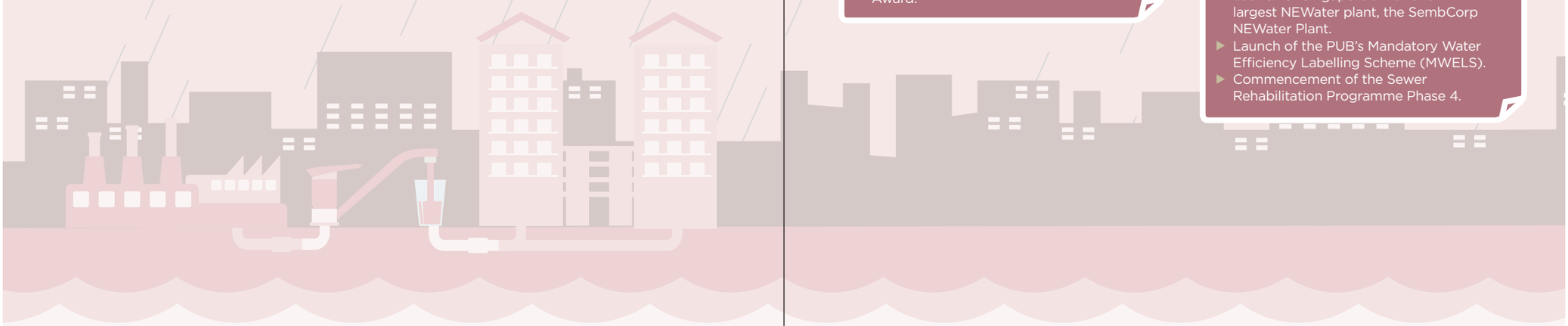
2005
- Commissioning of the SingSpring Desalination Plant, Singapore's first desalination plant.

2006
- Formation of the Environment and Water Industry Development Council under the MEWR.
- Commencement of the Private Sewer Rehabilitation Programme.
- Commencement of the Sewer Rehabilitation Programme Phase 3.
- Launch of the PUB's Active, Beautiful, Clean Waters (ABC Waters) Programme.
- The PUB is named as Water Agency of the Year at the Global Water Awards.
- Launch of the PUB's Water Volunteers Programme.
- The PUB wins the Singapore Innovation Award.

2007
- The PUB wins the Stockholm Industry Water Award.
- Commissioning of the Ulu Pandan NEWater factory.
- Completion of the Reservoir Integration Scheme.
- Introduction of the PUB's Watermark Award.

2008
- Launch of the inaugural Singapore International Water Week.
- Formation of the Inter-Ministerial Committee on Sustainable Development.
- Kim Chuan WRP phased out.
- Launch of the Institute of Water Policy under the Lee Kuan Yew School of Public Policy (NUS).
- Launch of the Marina Barrage.
- Completion of the PUB's first ABC Waters project at Kolam Ayer.
- Completion of the DTSS Phase 1.

2009
- Water Wally (the PUB's official mascot) makes its TV animation debut.
- Bedok WRP phased out.
- Introduction of the PUB's *ABC Waters Design Guidelines*, a handbook for industry professionals to incorporate ABC design features into their developments.
- Launch of the Changi Water Reclamation Plant.
- Launch of Singapore's fifth and largest NEWater plant, the SembCorp NEWater Plant.
- Launch of the PUB's Mandatory Water Efficiency Labelling Scheme (MWELS).
- Commencement of the Sewer Rehabilitation Programme Phase 4.



2000s

2010
- Launch of the PUB's long term water supply plans (2010–2060).
- Commissioning of Marina Reservoir (Singapore's 15th reservoir).
- Seletar WRP phased out.
- Expiry of Singapore's First Water Agreement with Malaysia.

2011
- Launch of the Punggol and Serangoon reservoirs (Singapore's 16th and 17th reservoirs).
- Ground-breaking for Singapore's second and largest desalination project.
- Revision of the Drainage Code to enhance Singapore's flood protection.
- The PUB hands over the Skudai water treatment plant, Gunung Pulai water treatment plant, Pontian pump house, and Tebrau pump house to the Johor State Government on 31 August.

2012
- Commencement of the PUB's 5-year plan to carry out drainage improvement projects to strengthen Singapore's flood resilience.
- Launch of the PUB's Bishan-Ang Mo Kio Park ABC Waters Project.

2013
- Launch of Tuaspring Desalination Plant, Singapore's second desalination plant.

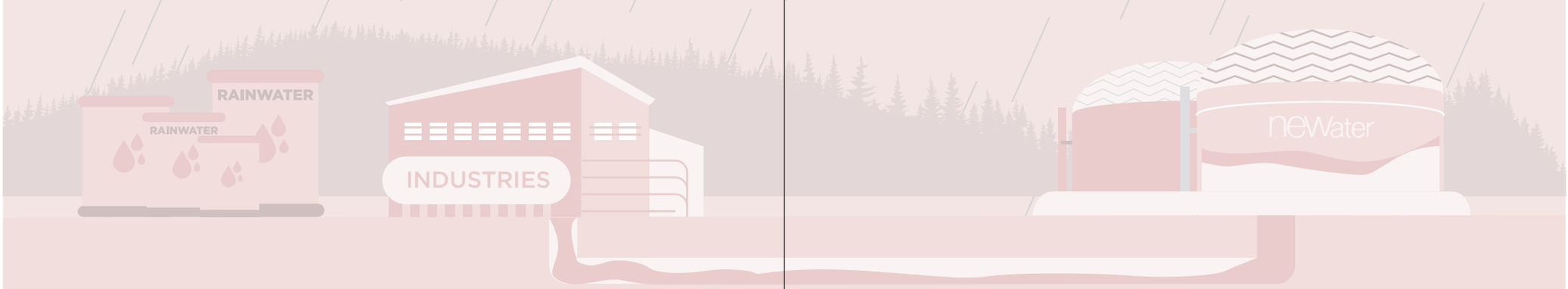
2015
- Commencement of construction work for the second NEWater plant in Changi.

2017
- Commencement of the Sewer Rehabilitation Programme Phase 5.
- Launch of the second NEWater plant in Changi in January.

2018
- Launch of the Tuas Desalination Plant in June.
- Launch of the SMART PUB Roadmap and the Singapore Water Exchange in July.

2019
- Commencement of the Smart Water Meter Programme Phase 1 in April.

2020
- Targeted completion of two additional desalination plants at Marina East and Jurong Island.



2010s

2020s

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APPENDICES

APPENDIX 1

Governance Tools of Singapore's Water Management System

Legal Instruments

Tool	Description
Water Agreements between Singapore and Malaysia (1961 and 1962)	Signed between the City Council of Singapore and the State of Johor in Malaysia, both agreements were enshrined in the Separation Agreement registered at the United Nations when Singapore became independent of Malaysia in 1965. The 1961 Agreement grants Singapore the full and exclusive right and liberty to take, impound and use all the water within the Gunung Pulai and Pontian catchments, and Tebrau and Scudai Rivers, up till August 2011. This agreement lapsed in 2011 and the waterworks under this agreement were handed back to Johor by Singapore. The 1962 Agreement provided for the supply of up to 250 million gallons of water per day from the Johor River to Singapore until 2061.
Environmental Protection and Management (Trade Effluent) Regulations	Subsidiary legislation of the Environment Protection and Management Control Act, which was formerly part of the Water Pollution Control and Drainage Act. It governs and regulates the discharge of wastewater into open drains, canals and rivers, and is administered by the National Environment Agency.
Public Utilities Act 2001	The Public Utilities Act 2001 repeals and re-enacts the then Public Utilities Act in order to integrate the Sewerage and Drainage Departments of the Ministry of the Environment as part of the Public Utilities Board, restructure the Board as PUB, Singapore's National Water Agency, and divest its role as the regulator of the electricity and piped gas industries.
Sewerage and Drainage Act and the Sewerage and Drainage (Trade Effluent) Regulations	Formerly part of the Water Pollution Control and Drainage Act, the Act and Regulations govern the provision, operation and maintenance of Singapore's sewerage system, including the treatment and discharge of industrial wastewater into public sewers. The Act and Regulations are administered by the PUB.
Water Conservation Tax	The tax was introduced in 1991 to discourage excessive consumption of water in both households and industries.

Executive Policies

Tool	Description
Water Supply	
Water Rationing	For two years in the mid-1960s, Singapore conducted water rationing exercises due to serious droughts and increasing water demand. The longest water rationing exercise lasted 12 hours on 7 May 1963. The exercises were relaxed only in January 1964.
Water Master Plan	The first Water Master Plan was drawn up in 1972. The Plan was most recently updated in 2016—the 2016 Water Master Plan is a 50-year long-term plan.
Industrial Water Programme	Industrial water was first introduced in 1966 with the construction of the Jurong Industrial Water Works by the Economic Development Board (EDB) as a cheap source of low-quality water to industries. Its objective was to help conserve potable water by reclaiming the final effluent from the Ulu Pandan Water Reclamation Plant. The industrial water produced would serve as an alternative source of water for industries in the Jurong/Tuas Industrial Estate, Tuas View and Jurong Island.
Water Pricing Policies	Singapore does not treat water as a public good and charges for its use. The original tiered pricing structure was replaced in 1997 by marginal cost pricing to recover the full cost of the production and supply of water, and to reflect the opportunity cost of using an alternative form of production.
Water Catchment Policy	Negotiated among several agencies (the PUB, EDB, Housing & Development Board and Jurong Town Corporation) that were competing for land use at various points in time, the policy initially set an urbanisation cap of 34.1% for development in unprotected water catchment areas. This policy was lifted in 1999.
Public Campaigns and Programmes	Awareness/education programmes and campaigns to encourage the public to conserve water by incorporating good water practices in their daily lives. Some examples include: Water is Precious (1971), Save Water Campaign (1995), and the 10 Litre Challenge (2006).

Tool	Description
Used Water	
Sewerage (Used Water) Master Plan and Implementation	To guide the development of sewerage facilities of the entire island. Under the Master Plan, the government divided the land into six used water catchment zones, based on the contours of the island, each served by a centralised water reclamation plant. Used water is treated to international standards before being disposed into the sea.
Sewer Rehabilitation Programme	The Sewer Rehabilitation Programme looked to check and rehabilitate all public sewers. Leaking sewers are a cause for concern, as the used water that leaks out will eventually find its way into the waterbodies.
Drainage	
Flood Alleviation and Prevention Programmes	To reduce flood-prone areas to meet the needs of rapid development.
Others	
Active, Beautiful, Clean (ABC) Waters Programme	The Active, Beautiful, Clean (ABC) Waters Programme aims to create beautiful and clean streams, rivers and lakes with community spaces for all to enjoy.
Research and Development (R&D) Initiatives	The Environment and Water Industry Development Council was set up under the Ministry of the Environment and Water Resources in 2006. As of 2016, a total of S$670 million has been committed to promote research and development (R&D) in environment and water technologies.
Public-Private Partnerships for Water Production	Examples: – Design-Build-Own-Operate (DBOO) Marina East Desalination Plant with Keppel. – Changi NEWater Plant with Sembcorp.

Institutions

Tool	Description
PUB, Singapore's National Water Agency	Statutory board responsible for Singapore's water management system.
Ministry of the Environment and Water Resources (MEWR)	Parent ministry of the PUB.
National Environment Agency	Statutory board under the MEWR. Its role in terms of water management is to prevent water sources from pollution.

APPENDIX 2

Policy Timeline—Water Catchment Policy

Timeframe	Historical Development/Milestone
1971	The Pollution Survey Unit was set up. Initially meant to serve the Kranji/Pandan Reservoir Scheme, it eventually oversaw all anti-pollution work in connection with the water supply.
1972	The Ministry of National Development (MND) announced that factory farms and flatted farms would be planned to reduce water pollution caused by pig waste in the catchment areas of the Kranji and Pandan reservoirs.
1974	Cabinet Discussion on high-rise pig farming.
1975	Introduction of the Water Pollution Control and Drainage Bill for more effective protection of water resources and prevention of water pollution. Population growth and rapid industrial and economic development in the past 10 years had led to a corresponding increase in water demand, and with rising affluence, a demand for a healthier and cleaner environment. In the Kranji/Pandan catchment areas, pig farms and some pollutive industries had to relocate to non-catchment areas. In the catchment areas, only non-polluting industries and activities were allowed. All used water from these premises, including trade effluent, would have to be discharged into the sewers to reduce and minimise the pollution of water in streams and canals, some of which fed into reservoirs. Authority for sewerage, drainage and water pollution control was vested in the Director of Water Pollution Control and Drainage, who would also have the powers to control the quality, extraction, storage and use of water in Singapore.
1977	Further discussion on the resettlement of farmers. The Sembawang Pig Farm under the Primary Production Department was aborted completely, as it was deemed more important to protect the supply of water than the rearing of pigs. An alternative pig farming area in Punggol was developed.
1982	Decision to phase out all nightsoil buckets by 1984 as the use of nightsoil buckets increased the hazards of infectious diseases. In addition, the workforce of nightsoil workmen was dwindling. Installation of the R2 waste treatment system.
1983	Introduction of the 1983 Catchment Policy; its key provisions were: • The Housing & Development Board was allowed to develop to its normal density of 198 dwelling units/ha. • The land area developed was restricted to 34.1% of the unprotected water catchment area, excluding the water surface. • A list of pollution control measures agreed between the Ministry of the Environment (ENV) and the MND.

Timeframe	Historical Development/Milestone
1983	Creation of Section 14A of the Water Pollution Control and Drainage Act, which prohibits the discharge of toxic substances into any inland waters. Penalties included fines and imprisonment.
1984	Pig farms were phased out.
1989	The PUB allows non-pollutive recreational activities, such as fishing and paddle boating, in reservoirs and catchment areas.
1999	The Water Pollution Control and Drainage Act was consolidated together with the Clean Air Act and the Drainage Act under the new Environment Pollution Bill. Part V of the Bill deals with water pollution control. • Under Clause 15, any person who intends to discharge trade effluent, oil, chemical, sewage or other polluting substances into any drain or land has to obtain a licence. • Clause 16 requires any occupier to treat such trade effluent before it is discharged. • Clause 17 prohibits the discharge of any toxic or hazardous substance into any inland water. • Clause 18 empowers the ENV to require any person who discharges any polluting matter onto any land or into any drain or sea to remove and clean up such substance or matter within a specified time. • Clause 19 empowers the ENV to require any person to take measures to prevent water pollution due to the storage or transportation of toxic substances or other polluting matters.
1999	Introduction of Pollution Control Measures for golf courses within water catchments. • Water quality of surface runoff was closely and regularly monitored. • Use of pesticides and chemical fertilisers in golf courses regulated to prevent pollution.
1999	The Review of the Water Catchment Policy concluded that water pollution control measures have been largely successful, therefore land in unprotected catchments could now be opened up for other uses beyond housing. • Urbanisation level cap and population density limit were also removed. • Water treatment plants upgraded to cater for water from developed areas. • Continued enforcement of stringent pollution control measures to prevent water pollution from community-based activities.

APPENDIX 3

The Production of NEWater

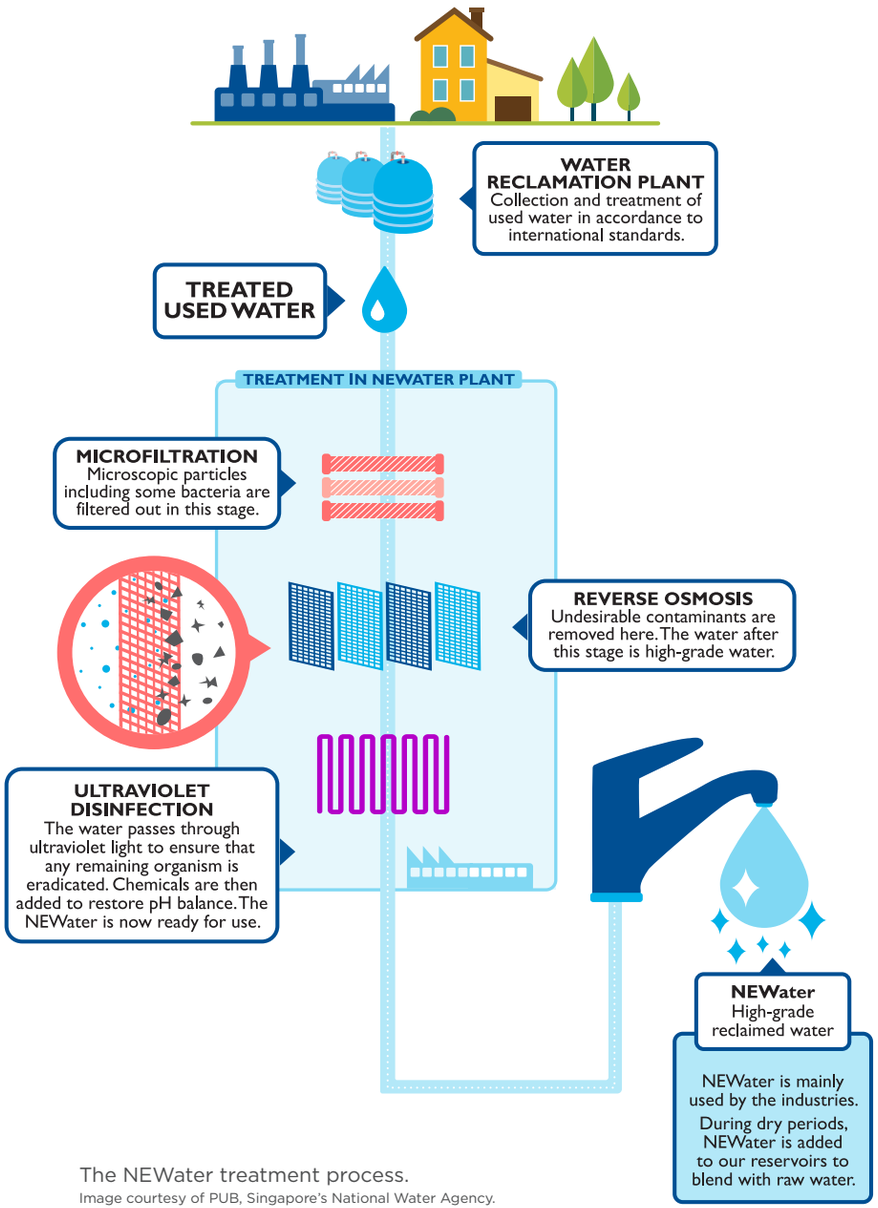
Source: PUB, Singapore's National Water Agency.

The first stage of the NEWater production process is known as Microfiltration. In this process, treated used water is passed through membranes to filter out suspended solids, colloidal particles, disease-causing bacteria, some viruses and protozoan cysts, which are all retained on the membrane surface. The filtered water contains only dissolved salts and organic molecules.

The second stage of the process is known as Reverse Osmosis (RO). In RO, a semi-permeable membrane is used, which has very small pores that allow only tiny molecules like water molecules to pass through. Consequently, undesirable contaminants such as bacteria, viruses, heavy metals, nitrate, chloride, sulphate, disinfection by-products, aromatic hydrocarbons, pesticides, etc., cannot pass through the membrane. Hence, NEWater is free from viruses and bacteria and contains negligible amounts of salts and organic matters.

Reverse Osmosis is a widely recognised and established technology that has been used extensively in many other areas. This includes the production of bottled drinking water and ultra-clean water for the wafer fabrication and electronics industries. Reverse Osmosis is also becoming increasingly popular as one of the technologies used in the desalination of seawater for human consumption. It is also used to recycle used water into drinking water on space shuttles and International Space Stations.

At this stage, the water is already of high-grade quality. The third stage of the production process acts as a safety back-up to the RO stage. In this stage, ultraviolet or UV disinfection is used to ensure that all organisms are inactivated and the purity of the water is maintained. With the addition of some alkaline chemicals to restore the acid-alkali or pH balance, NEWater is ready to be piped off to its wide range of applications.



The NEWater treatment process.
Image courtesy of PUB, Singapore's National Water Agency.

A Comparison of NEWater and USEPA*/WHO** Standards

Water Quality Parameters	NEWater	USEPA/WHO Standards
A) Physical		
Turbidity (NTU)	<5	5 / 5
Colour (Hazen units)	<5	15 / 15
Conductivity (µS/cm)	<250	Not specified
pH value	7.0–8.5	6.5–8.5 / -
Total dissolved solids (mg/l)	<150	500 / 1000
Total organic carbon (mg/l)	<0.5	- / -
Total hardness ($CaCO_3$) (mg/l)	<50	Not available
B) Chemical (mg/l)		
Ammoniacal nitrogen (as N)	<1.0	- / 1.2
Chloride (Cl)	<20	250 / 250
Fluoride (F)	<0.5	4 / 1.5
Nitrate (NO_3)	<15	10 / 11
Silica (SiO_2)	<3	- / -
Sulphate (SO_4)	<5	250 / 250
Residual Chlorine (Cl, total)	<2	4 / 5
Total Trihalomethanes (as mg/l)	<0.08	0.08 / -
C) Metals (mg/l)		
Aluminium (Al)	<0.1	0.05–0.2 / 0.2
Barium (Ba)	<0.1	2 / 0.7
Boron (B)	<0.5	- / 0.5
Calcium (Ca)	4–20	- / -
Copper (Cu)	<0.05	1.3 / 2
Iron (Fe)	<0.04	0.3 / 0.3
Manganese (Mn)	<0.05	0.05 / 0.4
Sodium (Na)	<20	- / 200
Strontium (Sr)	<0.1	- / -
Zinc (Zn)	<0.1	5 / 3
D) Bacteriological		
Total coliform bacteria (counts/100 ml)	Not detectable	Not detectable
Enterovirus	Not detectable	Not detectable
Heterotrophic plate count (CFU/ml, 35°C, 48 h)	<300	<500 / -

* United States Environmental Protection Agency
** World Health Organisation

APPENDIX 4

Deep Tunnel Sewerage System

Source: PUB, Singapore's National Water Agency.

The Deep Tunnel Sewerage System (DTSS) is an efficient and cost-efficient solution to meet Singapore's long-term needs for used water collection, treatment, reclamation and disposal. Conceptualised in the 1990s and managed by PUB, Singapore's National Water Agency, it was conceived as a cost-effective and sustainable solution to meet Singapore's long-term used water needs. The mammoth DTSS project will consist of a network of link sewers leading to two major, deep tunnels crisscrossing the island with three centralised water reclamation plants at the northern (Kranji), eastern (Changi) and western (Tuas) ends of Singapore, as well as outfall pipes.

Completed in 2008 at a cost of S$3.4 billion, Phase 1 of the DTSS comprises a 48-km-long deep tunnel sewer running from Kranji to Changi (i.e., eastern part of Singapore), a centralised water reclamation plant at Changi, two 5-km-long deep-sea outfall pipes, and 60 km of link sewers. The heart of the DTSS, the Changi Water Reclamation Plant (CWRP), is an advanced used water treatment plant. The treated water is discharged into the sea through deep-sea outfall pipes or channelled to the Changi NEWater factory on the rooftop of the CWRP's liquid treatment modules, where it is further purified through advanced membrane technologies into NEWater, Singapore's own brand of reclaimed water.

Construction of Phase 2 of the DTSS commenced in 2017. It extends the existing deep tunnel system to collect used water from the western and southern parts of Singapore. When completed in 2025, Phase 2 will have a conveyance system made up of 60 km of link sewers and 40 km of deep tunnels, as well as the Tuas Water Reclamation Plant, known as Tuas WRP. Similar to the Phase 1's CWRP, Tuas WRP will also be integrated with a NEWater factory.

The DTSS Phase 1 was crowned "Water Project of the Year" at the Global Water Awards 2009 in Zurich, Switzerland; it was recognised as the water project that made the most significant contribution to water technology and environmental protection. The annual Global Water Awards is one of the most prestigious symbols of achievement in the global water industry.

Components of the DTSS

- Link sewer network: The link sewers connect existing sewerage pipes from homes and industries to deep tunnel sewers. Constructed with depths ranging from 10 to 30 m, a trenchless method was used to minimise the disruption of activities above ground. Ranging from 0.3 to 3 m in diameter, the link sewers total about 60 km in length for each of the DTSS's two phases.
- Deep tunnel sewers: The tunnel sewers have diameters of 3.3 to 6 m and depths reaching 55 m. Eight and nineteen tunnel boring machines were used simultaneously to excavate these deep tunnels under Phases 1 and 2, respectively.
- Changi Water Reclamation Plant (CWRP): The CWRP is the cornerstone of the DTSS Phase 1. Sited on 32 ha of reclaimed land, the CWRP features an advanced, compact and covered used water treatment facility.
- Tuas Water Reclamation Plant (Tuas WRP): Sited on 68 ha of reclaimed land, the Tuas WRP will upon completion feature an advanced, compact and covered used water treatment facility. It will treat two used water streams—industrial and domestic—that will be conveyed in by a separate network of link sewers and tunnels.
- Outfall pipes: 5 and 12-km-long deep sea outfall pipes channel the excess treated water from the CWRP and Tuas WRP for dispersal into the sea.

Benefits of DTSS

Ensuring sustainability of NEWater

The DTSS is an important component of Singapore's water management strategy, as it allows every drop of used water to be collected, treated and further purified into NEWater, Singapore's own brand of reclaimed water. NEWater is a pillar of Singapore's water sustainability. NEWater, together with three other sources of water—water from local catchments, imported water and desalinated water—form Singapore's Four National Taps, which are the PUB's long-term water supply strategy to ensure a robust and sustainable supply of water for Singapore.

Singapore's largest NEWater plant to date is built on the rooftop of the CWRP, the first of its kind in the world. Integrating the NEWater plant with the DTSS allows for efficient, large-scale water recycling, thus ensuring the sustainability of NEWater.

The two phases of the Deep Tunnel Sewerage System.
Image courtesy of PUB, Singapore's National Water Agency.

Harnessing synergies

The PUB and the National Environment Agency are looking into harnessing potential synergies of integrating used water and solid waste treatment by co-locating DTSS Phase 2's Tuas WRP with an Integrated Waste Management Facility (IWMF). For example, the sludge generated from the Tuas WRP will be sent to the IWMF for incineration. Such integration helps to maximise energy and resource recovery while keeping the footprint compact.

Compact design and efficient land use

The compact design of the CWRP requires only one-third of the land area of a conventional plant. There is also no need for a buffer zone, as the plant modules are fully covered. Phase 1 of the DTSS replaces three of the existing WRPs and accompanying pumping stations, freeing up to 110 ha of land for other developments.

Phase 2, once completed, will free up another 40 ha of land space by replacing the existing WRPs at Ulu Pandan and Jurong, and intermediate pumping stations.[69]

Growing Singapore's industry capabilities

The DTSS Phase 1 involved over 300 local and international contractors, subcontractors and suppliers to work on the construction of the DTSS. The experience enabled them to build up their track records and pitch for larger-scale projects in Singapore and beyond. In order to deliver the DTSS Phase 2, given its scale and complexity, Singapore will again need to tap on the expertise of many local and international partners.

APPENDIX 5

The PUB's R&D Technology Domains of Interests[70]

- Biological Processes
- Water Distribution
- Watershed Management
- Water Quality Analysis
- Desalination and Water Reuse
- Sludge and Brine Management
- Chemical Redox Technologies
- Automation/Robotics
- Groundwater/Underground Caverns
- Decentralised Water Treatment Technologies
- Industrial Water Technologies

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WATER: FROM SCARCE RESOURCE TO NATIONAL ASSET

Water: From Scarce Resource to National Asset recounts Singapore's remarkable water story. Although surrounded by water, Singapore is one of the world's most water-stressed countries. Singapore's water system involves a delicate balancing act on two fronts. Firstly, the country seeks to maintain its imported water supply from Malaysia, while ceaselessly exploring alternative sources through technology and public mobilisation. Secondly, it has to balance land requirements for water catchments with competing needs for housing and industry. Demand is also calibrated to the thimbleful. As an expensive commodity, water is priced to reflect not just the high cost of storage, processing and distribution, but also its strategic value. Public education and community engagement were also used to manage demand. This study also examines how Singapore achieved a paradigm shift in its water management by using new technologies, such as membranes and desalination, new drainage and flood control systems, as well as innovations such as building reservoirs in urban areas.

"Every other policy has to bend at the knees for our water survival."

Lee Kuan Yew, first Prime Minister of Singapore.

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