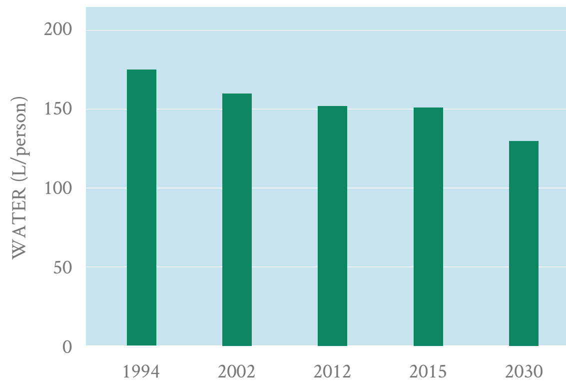
chapter

04

WATER RESOURCES AND SUSTAINABILITY

P. G. Rowe and L. Hee, *A City in Blue and Green*,
https://doi.org/10.1007/978-981-13-9597-0_4

In addition to 'green and clean' in the service of national identity, equality and attractiveness, sustainability of Singapore with regard to water supply and use is of strategic national concern. Indeed, it is expected to achieve this by 2061 when Singapore's remaining water agreement with neighboring Malaysia will end, even though imported sources from Malaysia account for 40 percent or so of overall supply as of 2009.[1] Moreover, sustainability in this regard is so strategically important that all other matters of national concern 'bend at the knee', so to speak, in abeyance to this single outcome and issue. At present Singapore is dependent upon what are called its 'four national taps' as its supply strategy. In addition to importation, 'local water catchment' provides some supply, largely by way of collecting and channeling rainwater to Singapore's 17 reservoirs via a network of rivers, canals and drains. Although water rich in terms of annual rainfall, unlike other places in the world, like Boston in the U.S. or Melbourne in Australia, with their abundant resources in dams in outlying areas, also at higher elevations than the cities proper, Singapore has a limited land and catchment area. Therefore, more conventional water storage, treatment and supply approaches are not feasible in face of the city-state's demand. Two compensatory sources of supply are so-called NEWater, Singapore's brand of reclaimed water, involving membrane and other cleaning technologies, and desalination of seawater. On the demand side, the government also actively promotes improved performance by way of active and successful demand reduction, largely in the form of individual conservation at the source of water use. This could be imagined as the fifth National Tap, an equally critical component to achieve sustainable water supply in the long run. Indeed, today Singapore is getting closer to the goal of 130 liters per person in daily use by 2030. The real genius and innovation, however, in Singapore's domestic water supply approach comes not so much from specific technical innovation as by way of overall conceptualization.



43. SINGAPORE'S DOMESTIC HOUSEHOLD WATER CONSUMPTION

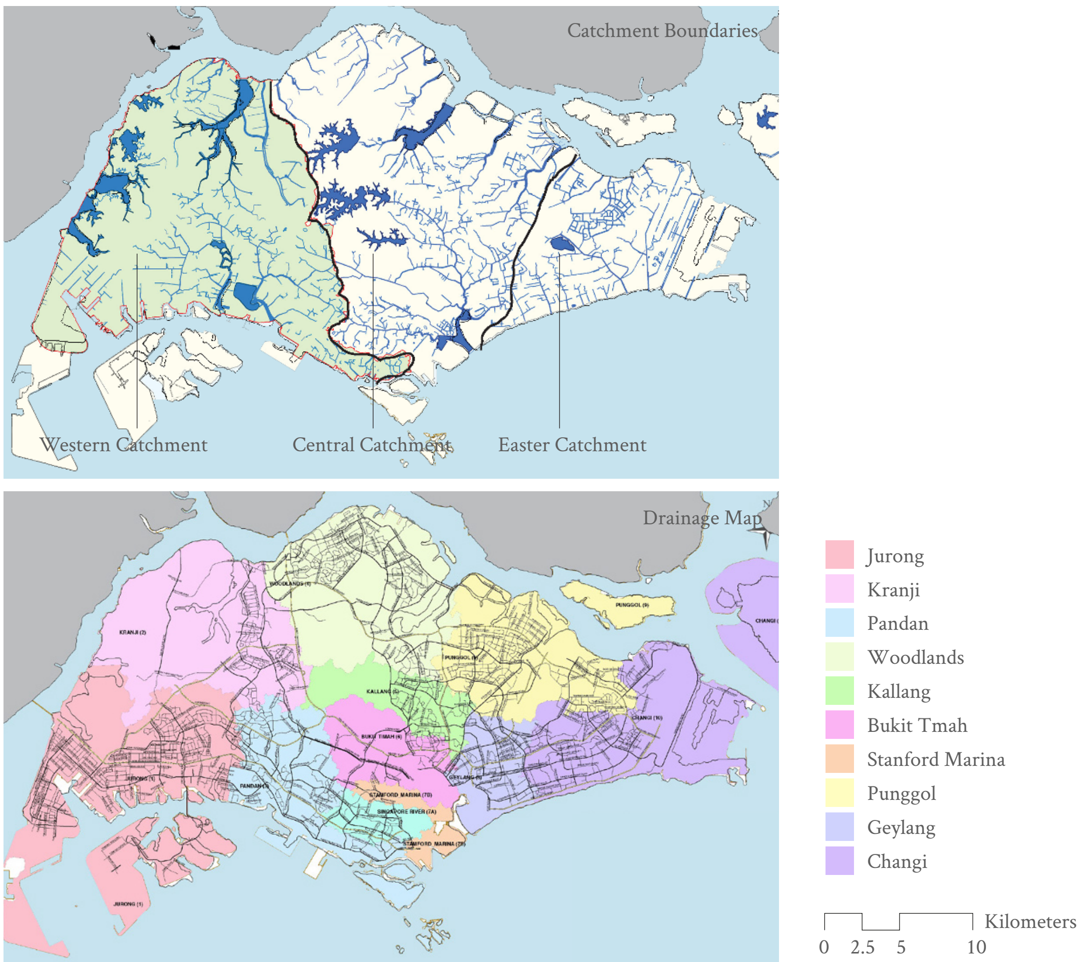
Instead of a large raw storage, treatment and supply system as elsewhere, use is made of a closed loop in conjunction with 'used water' instead of 'waste water' that is constantly re-cycling.

The colonial legacy of a separated storm water and sewage system of conveyance effectively sets the foundation for Singapore to continue to expand the drainage and sewerage network across the island. The fundamental principles of the closed loop system are to gather almost every drop of rainwater runoff, collect every drop of used water and recycle every drop of water more than once, thus obviating the need for large storage devices which Singapore lacks as a land-scarce city-state island. In terms of the energy-water nexus, the sewage stream is being re-cycled in the form of carbon extraction from waste and co-generation of electrical power to augment current capacities and help drive the requisite pumping required in the re-cycling efforts. This augmentation, of course, also helps lessen the load on imported sources of energy, like oil and gas, where Singapore continues to be dependent. Though not completely self-sufficient, the trading of one dependency in water for another in energy resources is clearly lessened. Finally, desalination and together with NEWater production further augments and 'tops up' so to speak, necessary overall domestic water supply. Several technically sophisticated desalination plants have been built or are under construction at various ends of the island to perform this function. As mentioned it is the co-ordination of use and implementation of this multi-source approach and the radical re-thinking of conventional municipal water storage and supply that has been Singapore's signature international contribution and where it truly leads, rather than in the membrane, desalination and other treatment technologies *per se*. Furthermore, although not completely implemented at this writing, sufficient proof of concept and several working plants and conveyance systems will ensure success, probably well before the 2061 deadline. In addition, significant aspects of the radical overall approach seem to be transferable to other water-scarce urban situations elsewhere in the world. What is excluded from this depiction, however, are virtual water flows ascribed to Singapore from elsewhere in the world in order to support agriculture and industrial products used by Singaporeans. While likely to be sustainable with regard to important elements of domestic demand like household use, the city state is not and likely will not be fully sustainable with regard to virtual water consumption, like many other nations in the world.

a. SINGAPORE'S CONSTRAINTS AND OPPORTUNITIES IN WATER RESOURCES

Largely due to its relatively small size and lack of a full complement of natural resources, Singapore faces a number of constraints as it attempts to achieve water sustainability by 2061. By contrast, there are also some advantages or opportunities that can be exploited further. At present the land area of Singapore is 722.5 square kilometers, including some 140 square kilometers of reclaimed land, or around 24 percent of the land area since 1959, constructed mainly in the west and east.[2] Despite this relatively small area and dense land occupation at around 7,042 inhabitants per square kilometer, Singapore has its rainwater and run-off storage capacity appreciably through construction of reservoirs in the centre of the island and at river mouths. Early stages of this were described in chapter 2, but more recent advances have been made from fourteen reservoirs in 2005 to seventeen reservoirs as of today.[3] With the recent building of the Marina Barrage and both the Punggol and Serangoon Reservoirs the drainage catchment area now covers roughly two-thirds of the national territory.[4] By contrast, Melbourne in Australia, another city with a comparative emphasis on 'green and blue' developments leveraged its spatial advantage to easily tap into its protected and forested catchments to harvest water stretching along the Great Divide, a substantial area in the middle of the State of Victoria. Recently, however, climate change and drought conditions revealed some vulnerabilities with regard to adequate supply, despite the large latent capacity of the catchment areas.[5]

Unlike other large cities, Singapore does not enjoy abundant groundwater supplies. Indeed, as described earlier, serious consideration of groundwater as a potential source of constant supply has been ruled out, even though the PUB continues to monitor and look into the possibility.[6] By contrast annual rainfall is relatively abundant at around 2,400 mm per year in Singapore's tropical location, as is sea water, surrounding the island. One issue, however, with the tropical monsoonal conditions are the peaks and valleys in precipitation, where supplies can dry up between bouts of intense rainfall and catchment. Longer term droughts, like the one that afflicted the island in 1963 may be uncommon but cannot be ruled out entirely. The weather can also influence the relative salinity and other chemical compositions of reservoir and estuarine water services as well, posing potential problems for reliable treatment processes. As a corollary to this, fluctuations in electrical demand associated with desalination processes and at varying levels of salinity can effect operating efficiencies of treatment plants. Clearly Singapore must make a trade-off between largely imported and often costly energy resources in its water sector, especially with the use of desalination technologies. By contrast, though, the city state benefits from the British legacy of a separated and dual storm-water and sewage system, particularly with regard to down-line treatment. At the moment energy requirements per cubic meter for domestic water treatment is about 0.66 kwh per cubic meter of water, but is expected to double with technical



44. MAPS PERTAINING TO SINGAPORE'S CATCHMENT AND DRAINAGE SYSTEM

shifts towards desalination and water reuse, before reaching a level of something like 0.75 kwh per cubic meter in the longer term.[7] To put this in context, it has been estimated that about two percent of the Singaporean electricity demand is already dedicated to water and treatment processes.[8]

Singapore's concerted efforts towards sustainability in domestic water consumption, however, are dwarfed by the imputed virtual water components of food and industrially produced products. At present this seems to amount to about 20 times the current blue water supply. Here virtual water is a term that embraces the amount of water used to produce a certain good or product. It was first introduced during the 1990s to account for the limitations of water scarce regions which imported food grain grown with other's water.[9] From this the broader concept of a water footprint was developed, allowing calculation of the amount of virtual water in commodities of various kinds, such as the ratio of the total volume of water used to the quantity of production.[10] More basically, a water footprint has three components. They are: the green water component or the volume of rainwater evaporated or incorporated into products; the blue water component or volume of surface or groundwater evaporated or incorporated into a product or returned to other catchments or the sea; and the gray water component, or the volume of water needed to dilute loads to such an extent that they reach certain water quality standards.[11] Anyway, Singapore's small scale, particularly in relationship to its largish population effectively precludes it reaching a sustainable condition with regard to virtual water. As described in chapter 2, during times in the past Singapore was far less numerous in population and did, in fact, reach levels of self-sufficiency in food production, mainly from small family-owned farms.

	2010	2060
DOMESTIC	45%	30%
NON-DOMESTIC (POTABLE)	33%	42%
NON-DOMESTIC (NON-POT.)	22%	28%
NON-DOMESTIC (TOTAL)	55%	70%
PER CAPITA	154 LITRE/DAY	130 LITRE/DAY (2030)
TOTAL (MILLION GALLONS/DAY)	380 (100%)	860 (100%)

45. PROPORTIONS OF TOTAL AND SEGMENTED WATER USE, 2060 PROJECTION

b.

SINGAPORE'S FOUR NATIONAL TAPS

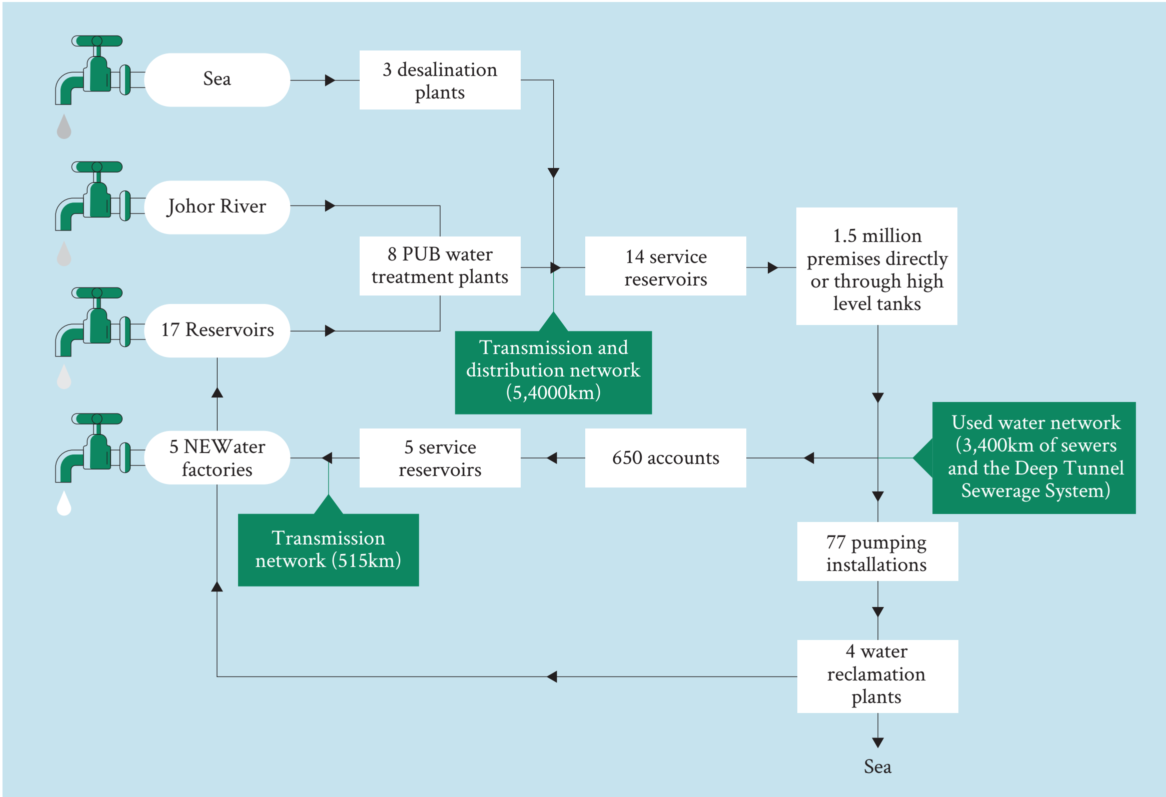
On the resource side, Singapore relies for progress towards water sustainability through its four taps, plus concerted efforts to manage local water consumption.[12] The first tap is supplied by importing water from Johor in Malaysia under a series of water agreements, briefly described earlier. This tap is estimated to provide 40% of Singapore's water demand, corresponding to 250 million cubic meters per year as assumed by Lenouvel et al. in 2013.[13] In this process quality drinking water is produced from freshwater by way of conventional water treatment processes. Despite having the source of imported water, the Singapore government felt the need to be more sustainable, and had begun to intensify its efforts in the 1970s to diversify the sources of water supply. This is being undertaken through the establishment of the additional National Taps.

The second water tap relies on rainwater catchment and Singapore's rainwater and run-off storage system described earlier. A clear aspect of the viability of this tap also goes back to the clean-up programs of the early Republic, described in chapter 2 and to Lee Kuan Yew's abiding interest in Singapore being 'clean and green'. Today development of harbor and industrial activities are concentrated in the south and southwest of the island and away from the main water courses and reservoirs. Singapore has successfully developed a total of 17 reservoirs and expanded the water drainage catchment area to two-third of the nation's land area. The energy footprint of this tap is also quite small at around 0.25 kwh per cubic meter of water.[14]

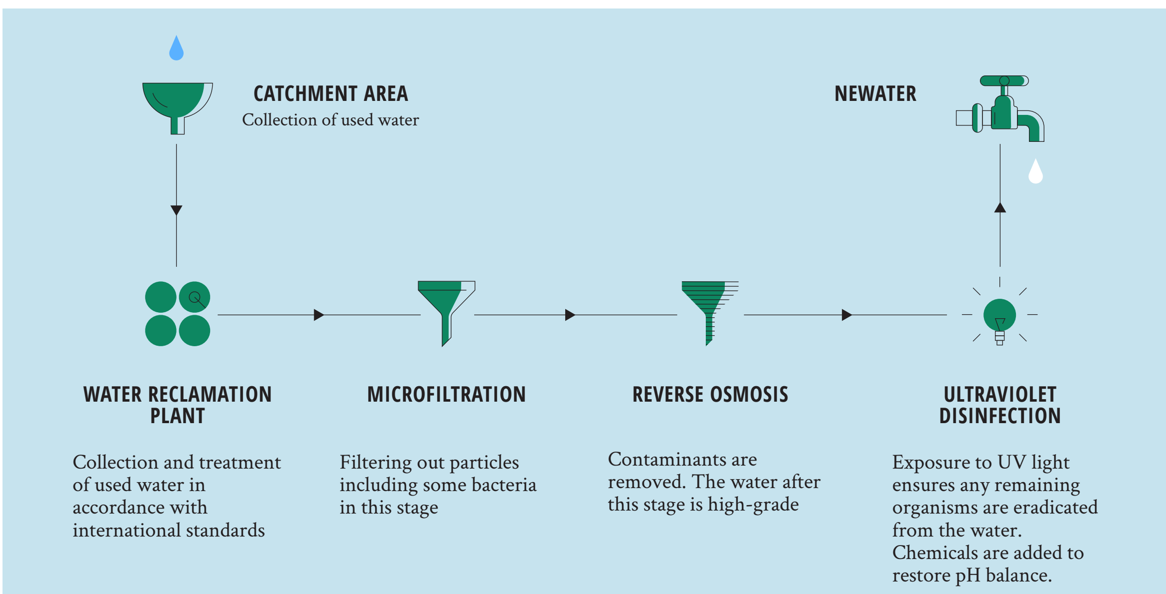
The third water tap has relied, since 2003, on water reuse and the so-called NEWater Initiative. This currently can supply up to 40 percent of Singapore's water needs. The NEWater journey started way back in the 1974 when then-Public Utilities Board started experimenting on water reclamation and treatment, however, it did not take off because the technologies then were too costly and unreliable. It was only in the 1990s when technological advancements had brought down the cost of membranes, that PUB revisited the possibility of large-scale water recycling. Through overseas study of other cities' technologies and thorough feasibility study, the engineers, in 2000, eventually designed and constructed a demonstration water reclamation plant in Bedok, a milestone that led to the creation of NEWater, Singapore's brand of reclaimed water. Fundamentally, NEWater involves a production process for treating used water, including effluent, through a succession of stages, resulting in drinkable water meeting the highest of standards. The first stage of the process is known as microfiltration.[15] It is when the treated used water is passed through membranes to filter out solids, colloidal particles, disease-carrying bacteria, some viruses and *protozom cyots*. The filtered water that goes through the membrane contains only dissolved salts and organic molecules. The second stage of this NEWater production process is known as reverse osmosis, where a semi-permeable membrane is used. This semi-permeable membrane has very small pores in it which only allow very small molecules like water molecules to pass through. Consequently, undesirable contaminants such as bacteria, viruses, heavy metals, nitrate, chlorides, sulfates, disinfection by-products, aromatic hydrocarbons, pesticides, etc., cannot pass though the membrane. In other words, NEWater is reverse osmosis water and is relatively pure and contains negligible amounts of salts and organic matter. At the onset of the third stage, the water is already of a high quality and it acts as a further supply back-up to the reverse osmosis. In this stage ultraviolet disinfection is used to ensure that all organisms are inactivated and the purity of the water product can be guaranteed. Before storage of NEWater in tanks, the water balance of pH and the addition of some alkaline chemicals takes place to restore the acid alkali pH balance. It is then ready to be piped off to a wide range of applications mainly for non-potable use by the industrial sector such as wafer fabrication plants which require ultra-clean water. About 2 percent of NEWater is injected into reservoirs to blend with the raw water, before it is sent to the conventional waterworks for treatment and supply to customer taps.[16] Such a process of indirect consumption of NEWater, in addition to extensive public education and outreach efforts, is part of PUB's strategy to overcome aversion by the public to the reclaimed water.[17] The accompanying diagram illustrates the process of NEWater production. The tertiary wastewater treatment involved with NEWater consumes relatively high amounts of energy due to the intensification of the nutrient removal process.[18] In some places, for instance, such advanced wastewater treatment processes are highly energy intensive, with demand ranging from 0.39 up to 3.74 kwh per cubic meter of water. In Singapore the energy demand is on the order of 0.95 kwh per cubic meter of water, not very high but, in aggregate, significant.[19]

The fourth water tap relies on seawater desalination with, in Singapore, the commissioning of its first two plants in 2005 and 2013, with water production capacities of 50 and 115 million cubic meters per year.[20] Currently, the share of the desalination tap in water supply has been estimated to be approximately 8% of the total, with an assumption of imported water providing 40% of the water supply and rainwater harvesting at 30% .[21] The stated capacity of the three desalination plants combined amounts to 130 mgd that can meet up to 30% of Singapore's water demand,[22] but with high amounts of energy input at about 4.10 kwh per cubic meter of water, or about 74 percent of the total amount of energy expended by Singapore's water sector.[23] There are also different configurations of desalination. In the Singaporean context one of the most promising is the variable salinity desalination concept, devised to respond to the weather-variable conditions within catchment areas described earlier, especially in estuarine circumstances. There levels of salinity can vary substantially, such that harvesting needs to respond to the variation and in a timely fashion. Instead of remaining idle during periods of high overland flow and freshwater infiltration into a catchment area, the desalination mode is altered in response.[24] Overall, the process still involves screening, microfiltration, reverse osmosis and disinfection, as shown in the accompanying diagram, but with modes that respond to the levels of total disposable solids and salinity levels to product potable water that meets WHO and USEPA' Drinking Water Guidelines and Standards'.[25] The advantages of the variable approach include: much lower energy consumption through the mode switching and also significantly lower capital an operating costs.

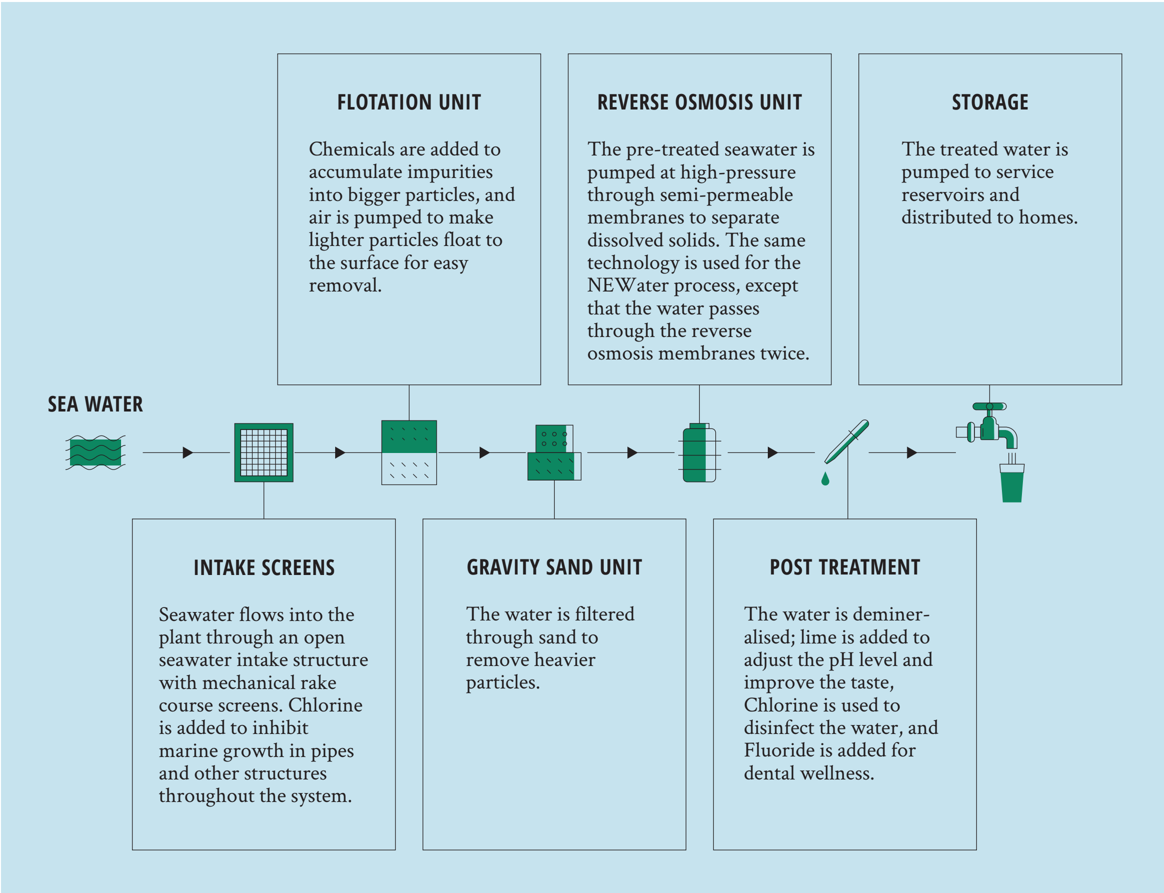
Other versions of desalination technology consist of essentially two kinds. They are: reverse osmosis and combined electrodialysis-electrodeionization processes. Reverse osmosis has been around since the 1970s and was the technology, discussed in chapter 3, though defective, that gave impetus to Singapore's conviction to pursue non-conventional sources of water supply. The process involves forcing seawater against a water permeable membrane which prevents dissolved salts and minerals from getting through.[26] However, it has a couple of inherent economic and technical limitations that will curtail its future use. First, the feed pressures are very high requiring substantial energy. On average 3.5 kwh per cubic meter of water are required. Second, pressures



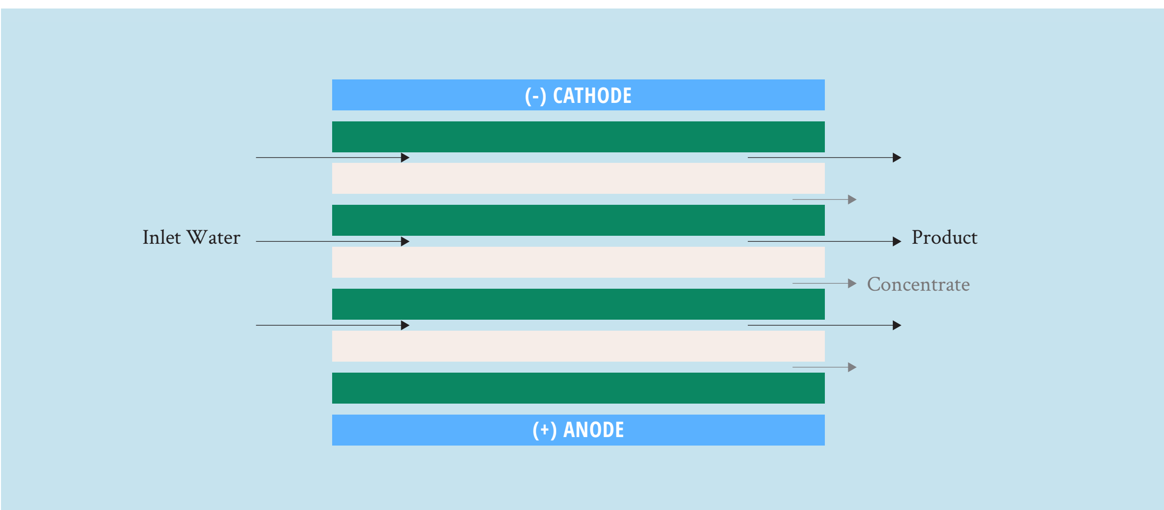
46. SINGAPORE'S FOUR NATIONAL TAPS



47. NEWATER DIAGRAM



48. DESALINATION DIAGRAM

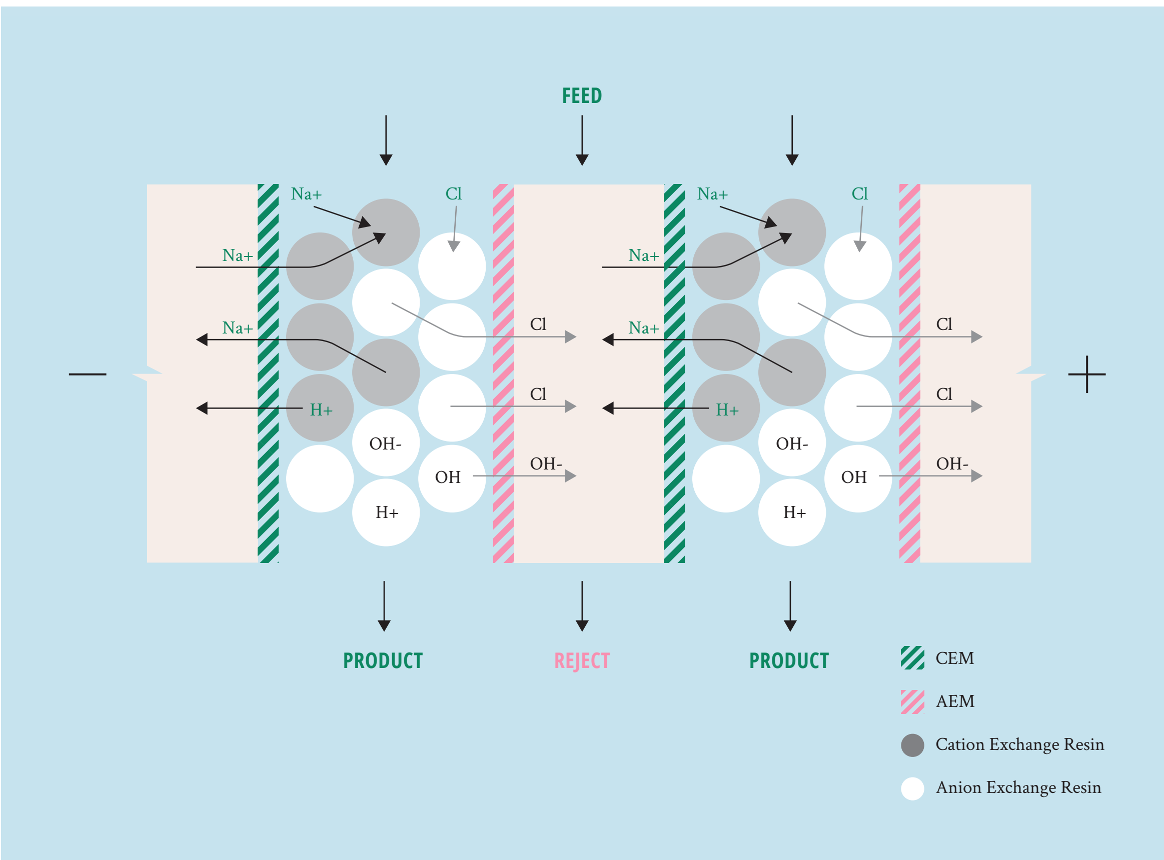


49. MICROFILTRATION SCHEMES AT WORK

can also cause serious deterioration of membranes requiring relatively constant replacement. By contrast the electrodialysis-electrodeionization schemes are far less energy consuming, testing at 1.8 kwh per cubic meter of water. In Singapore this technique was pioneered by Evoqua Water Technologies, previously known as Siemens Water Technologies, as a part of the 2007 'Singapore Challenge' competition which they established.[27] Technically, electrodialysis is an electrical separation process which selectively removes salt ions based on their electrical charge by transferring them through semi-permeable ion exchange membranes charges with a direct current voltage. The seawater separates into the product water with salt ions removed along with a concentrate with salt ions. However, flow through the series of electodialysis modules results in salt content that remains present but is too low for further removal by electrodialysis. Then electrodeionization takes up involving the transfer of solutions through semi-permeable membranes charged with electrical potential but with the use of exchange resins which increase the efficiency of transfer. The advantages of the combined electrodialysis-electrodeionization method over reverse osmosis are fairly obvious. It includes: lower energy expenditure, a tolerance of feed water of lower quality and a water product recovery rate that is higher. Further innovation of membrane technologies are also under serious investigation, including ceramic membranes and nano-filtration membranes, both of which seem likely to be cheaper to produce.

One of the main proponents and entrepreneurs in the water industry is Olivia Lum. She started off her business life as a child, working in a rattan factory and selling in the streets at an early age.[28] Determined to go into business she then trained as a chemist at the National University of Singapore, thinking this was a strong way of making a career in business. During the onset of the Asian economic crisis she worked as a chemist for Glaxo Pharmaceuticals and became interested in water technologies. In 1989 she left Glaxo and founded Hydrochem an early version of Hyflux, her current firm, using personal assets in order to raise the start-up capital for an enterprise in the Tampines Industrial Park. Starting off with only a staff of one clerk and one technician, she worked towards realizing the potential of membrane technology. In 2002, Hyflux was awarded a contract to build Singapore's third NEWater plant by the PUB in Seletar and in the following year, was awarded to build Singapore's first large-scale seawater desalination plant - the Singspring Desalination Plant - in Tuas. Subsequently, Hyflux again won the bid for the PUB's tender to build the country's second desalination plant. After some 29 years in business, Hyflux has successfully constructed some 1,000 plants of various sizes all over the world and helped put Singapore at the very forefront of the water treatment industry. Lum's efforts, though not literally inventing membrane technology and associated desalination technologies did put the general approach on the map, as it were, as far as large-scale projects were concerned. At present she is involved in producing her own brand of oxygen-rich water under the ELO brand and still concentrates on what for her are the two important aspects of the water resource business: cleaning and public health. One of the major hurdles that needed to be overcome was to gain the public's confidence in the safety and reliability of reused water.

In addition to these four taps, as mentioned, Singapore also embarked upon a strong program of water conservation and management, with the aim of reducing domestic household demand to an average of 130 liters per day in 2030 down from its current level of 151 liters per day per person (as of 2015).[29] Primarily conservation efforts have revolved around intense public education efforts, including exhibitions with elaborate explanations about the impact of various water-conserving technologies and strategies for individual and family use. Indeed, the PUB has been very active in these regards, especially among and with children a route that appears to catalyze further involvement among adults as well.[30] In the future, the present conservation goals appear to be realistic. In addition, among the taps, NEWater seems likely to account for 55 percent of domestic water needs by 2061 with 40 percent through five plants at the end of the year and desalination will likely supply 30 percent of demand by 2061. This will also add to the needed energy budget, though with greater efficiency. The Singapore Government aims to increase the water catchment area to 90% of Singapore's land area, up from about 66% of current water catchment area. Overall, the goal of sustainability by 2061, if not before, appears likely if not almost certain to be achieved.



50. DIAGRAMS OF ELECTRODIALYSIS – ELECTRODEIONIZATION

51. TUAS WATER TREATMENT MEMBRANE TECHNOLOGY AT WORK

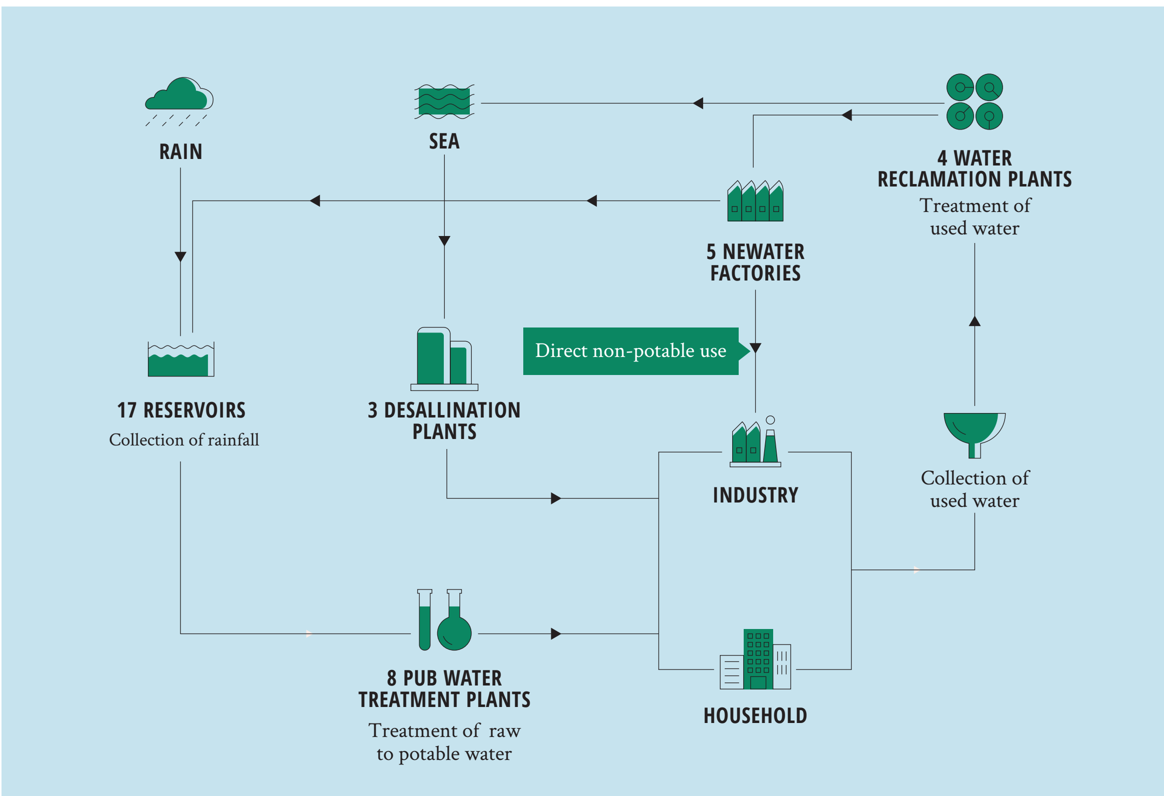
C.

SINGAPORE'S CLOSED LOOP SYSTEM

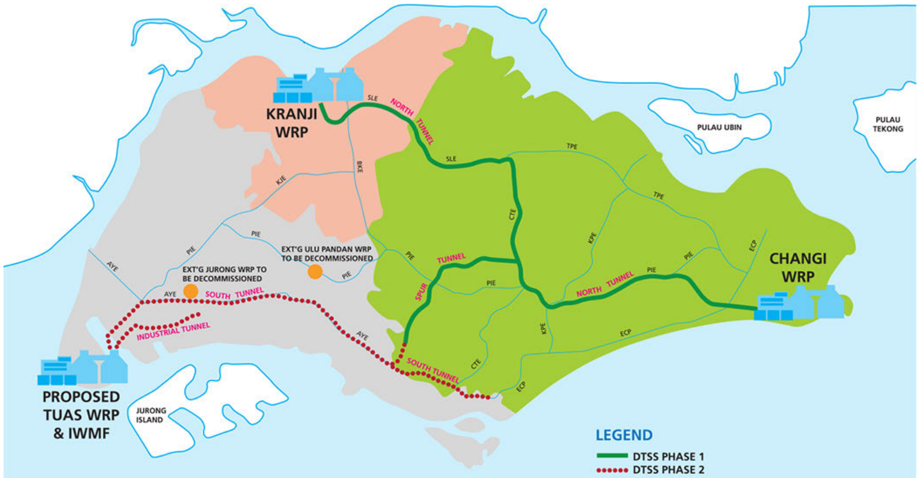
As indicated in the accompanying diagram, the crux and radical aspect of Singapore's approach to domestic water sustainability is the arrangement of the four tap technologies, plants and distribution networks into a closed loop system, where the Unaccounted for Water (UFW), mainly consists of water lost through leaks, stands at 5 percent, among the lowest globally. Consequently, the break with other conventional approaches to water supply is the constant re-cycling and reuse of water in the overall system, which theoretically remove the need for large areas of reservoirs and conventional treatment plants often adopted by many countries in the world. Also, as the network increases to serve expanded populations, so does the useable water storage capacity, making the entire system viable over time, in theory if not in practice. Central to Singapore's approach is naming and popular acceptance of 'used water', *in lieu* of 'waste water' and because of this, a capacity to re-cycle and reuse almost every drop of water on the island. Also key here is the harvesting and use of water in and from urban rather than more pristine circumstances. This is considerably different from conventional water supply regimes in places like Boston and Melbourne, where water harvesting is largely if not totally confined to catchment areas which are preserved as such and separated away from potentially contaminating other uses. This change in the spatial logic of water harvesting and potable water reuse is both a liberating and persistent feature of the Singapore approach. It does not mean, however, that the nation's catchment areas that have been well-defined and at least partially protected for years will fall away as sources of water supply for they will not. It also means that reservoirs for long-term diluting retention of large volumes of water, like the Marina Barrage, close to very urban adjacent land uses and sources for NEWater production will be maintained and become something of a new norm in the closed loop system of reuse and delivery.[31] In short, the indigenous three taps of Singapore's supply resources will remain with the emphasis in the use of one over the others determined by other related factors such as energy use and technological reliabilities.

The reduction of energy dependence in the water sector has been taken up by local authorities, largely under the umbrella of the Water Industry Program Office in partnership with the private sector and university research capacities. This involves at least three initiatives. The first is reduction of desalination energy needs through grant research by Evoqua Water Technologies among others. The second involves an increase of water catchment area to 90 percent of the island territory and with the use of variable salinity technologies to collect and treat water from estuaries.[32] The third is reduction of sludge processes, also involving pre-treatment from reverse osmosis by membrane bio-reactors. The PUB has also increased the integration of energy systems in water facilities again in three ways. First by involving increased optimization of biogas production from sludge digestion in used water treatment plants. Second by using production of energy through turbine technology in desalination plants. Third by offsetting operational costs of producing clean water and electricity through system integration between a power generation plant and a water reclamation plant. Independent study has shown that the long-term target of 0.75 kwh per cubic meter of water seems likely to be achieved, especially with suspension of reverse osmosis and reliance on breakthrough innovation in ion exchange and biometrics.[33]

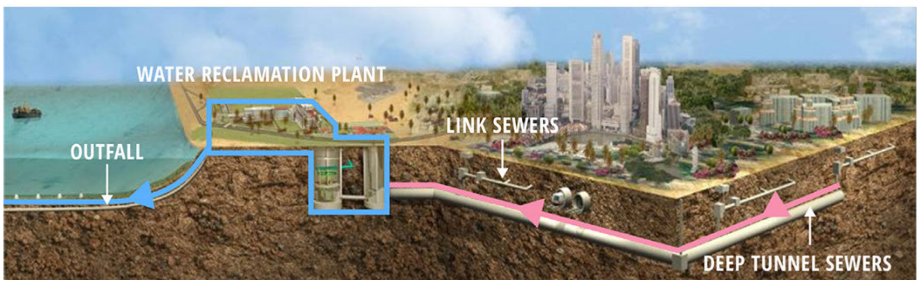
As mentioned here, the evolution of the Singapore water convergence and treatment system has been incremental from its early trials and beginnings even as far back as the 1970s. Indeed, it is through the various steps in the process, the discoveries made and the successive improvements incorporated that Singapore has made an indelible mark on the contemporary enterprise of the urban water sector and water industry. Currently another instance of this is being made through the island-wide Deep Tunnel Sewage System (DTSS) under the auspices of the PUB. Before its design and implementation the used water system of Singapore involved six water reclamation plants and some 130 sewage pumping stations. With the DTSS the scattered pumping stations can be progressively phased out and replaced with a single large diameter tunnel which conveys used water flow by gravity. The used water is then pumped up only once at a centralized pumping station located at two water reclamation plants located at the eastern and western part of Singapore. The scale economy of this approach is cost effective compared to the older and existing infrastructure. By reduction of surface facilities it also frees up valuable land for other higher-valued development. It also ensures adequate long-term convergence and treatment capacity, while presenting a more robust, reliable and resilient used water system.[34] In effect, the DTSS is becoming the super-highway for used water. Construction of the DTSS is being pursued in two phases. The first phase, completed in 2008, comprised the Changi plant of 176 million gallons per day in the east of the island and is made up of 48 kilometers of deep tunnel sewers and 60 kilometers of linked sewers. The second phase, commenced in 2014, will feature a similar 176 million gallon per day plant plus 25 million gallon per day NEWater capacity at Tuas in the west of the island. It is also comprised of 40 kilometers of deep tunnel, some three to six meters in diameter and 60 kilometers of linked sewers, around 0.3 to three meters in diameter.[35] These large tunnel pipes are constructed using tunnel boring machines through the rock and mixed-face substrate of their routes through the island. Remote operated vehicles will be used for inspection and fiber optic cable will be embedded into the lining of the tunnels for monitoring of structural adequacy. With airflow also present in the tunnels, odor nuisance is mitigated through air management facilities located at junctions with the link sewers. Management of these engineering undertakings will use Building Information Modeling (BIM) to take advantage of coordination during construction and future asset management system. The accompanying map and diagrams present aspects of the system and the location of three treatment plant and NEWater reclamation facilities at Kranji in the north, Changi in the east and Tuas in the west. Integration of energy and water management approaches are also being intertwined with the DTSS, as described earlier.



52. SINGAPORE'S WATER CLOSED LOOP SYSTEM



53. MAP OF THE DEEP TUNNEL SEWERAGE SYSTEM



54. SECTION OF THE DEEP TUNNEL SEWERAGE SYSTEM

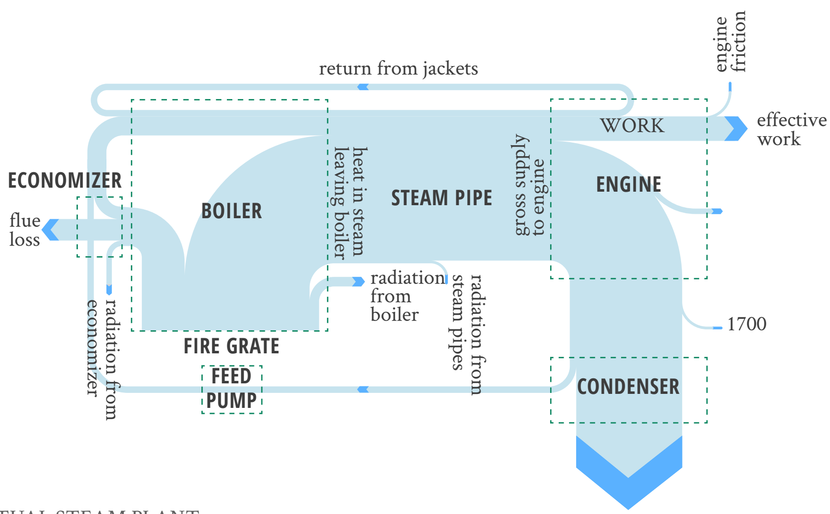
d. STOCK-FLOW DEPICTIONS

Looking across available data, the propagation of domestic to non-domestic water use in 2010 or thereabouts was 45 percent to 55 percent, with the latter number comprised of 33 percent potable water to 22 percent non-potable water. The bulk of water use was in domestic at about 43% whereas commercial and industrial each takes up about 26% of Singapore's water use. As noted earlier the per capita water use was 151 liters per day per person on average. Projections show that these numbers change appreciably for 2061 with over a doubling of total water demand and an apportionment of 30 percent in domestic use and a rise to 70 percent of the total for non-domestic use, which consists of both commercial and industry use.[36] The per capita use is estimated to be 130 liters per person per day, based essentially on a level likely to be reached by 2030. Returning to Singapore's four taps of sources of supply, in 2010 NEWater accounted for 19 percent of total use is also proportioned heavily in favor of industry, with only six percent for potable household use.[37] Water from desalination, accounting for 25 percent of total use is directed in the opposite direction, with 60 percent for household use and 20 percent each for industrial and building use. Water piped directly from Johor by sales accounted for 28 percent of use also again weighted strongly to household use at 54 percent, with 23 percent again evenly distributed for industrial and building use. The amount of unaccounted for water in this inventory is only five percent, a further testament to the closure of the water loop across the island.[38] Changes in these proportions in 2061, at least as projected, are also dramatic with the absence of piped water from Johor and Singapore aimed to increase the capacity of NEWater to meet up to 55% of the water demand, while up to 30% of the water demand will be met by desalination.[39]

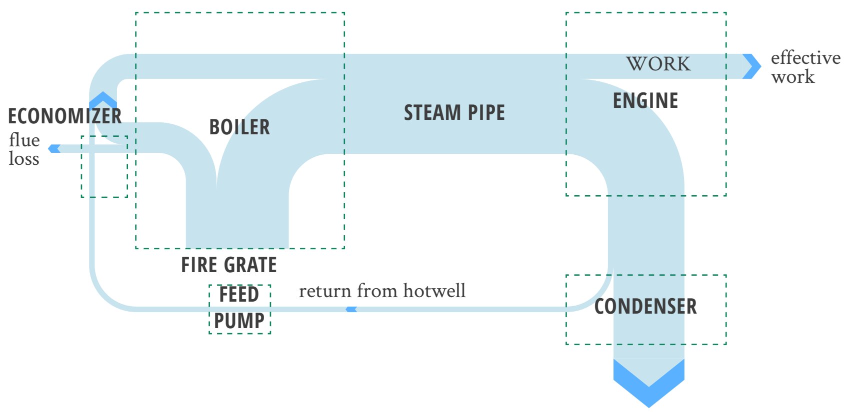
Another way of accounting for water use and in relationship to other resources as well, like energy and land, is through what are called Sankey Diagrams. These diagrams, such as depicted here, are flow diagrams, with the width of areas shown in direct proportion to the flows of different quantities of resources, from initial raw inputs to the results of production in the form of industry, commercial and domestic uses in this case. These flow diagrams are named for an Irish captain by the name of Mathew Henry Phineas Riall Sankey who originally used this type of diagram to describe the steam engine and its relative efficiencies with regard to energy inputs in 1898. In a rather simple diagram he depicted a wide band of inputs on the left-hand side with output in the form of propulsion on the far right-hand side, and various forms of waste emanating from the process along the way, such as smoke, friction, alternator flare and massive amounts of condensation.[40] Another notable diagram of similar type was drawn up by Charles Minard in 1889, depicting Napoleon's Russian Campaign and actually pre-dating Sankey's diagram.[41] Nevertheless, these diagrams have been used subsequently, largely to represent energy and other basic resource inputs along with corresponding outputs and losses in efficiency or its equivalent. Unfortunately, at the time of this writing, there was not sufficiently accurate available data to construct a complete and meaningful Sankey diagram for Singapore across land, water and energy demand.

There was, however, availability and sufficiency of data to reflect dollar amounts expended by each use sector for its utilities, rather than literal physical usage. In other words, dollars expended becomes a proxy for physical consumption and a way of showing relative importance to the Singaporean economy. This kind of mixed stock-flow diagram also introduces the useful idea that resource flows are, in fact, tied to specific land uses and, more generally, show a relationship among utilities and land in a highly constrained Singaporean context. More specifically, this chart shows expenditures on water and electricity in Singapore, based on sales to commercial, industrial, residential, transport and other uses.[42] There is relatively balanced usage among all sectors, although it must be noted that similar expenditures does not necessarily equate to similar consumption. For example, in electricity sales, the difference in rate structure for each sector is substantial, so while commercial users consume fewer kilowatt-hours of electricity, the total expenditure by commercial users appears to be greater than that of industry. Electricity and water are routed to residential, commercial and industrial sites, which constitute only a portion of Singapore's land use. It is interesting to note that while a small share of land devoted to commercial buildings, their resource consumption is still significant, which speaks to dense commercial development patterns, Much more land is devoted to industrial and residential purposes. Though both utilities are critical, it turns out that electricity pricing is much higher, so that electricity sales dwarf water sales.

However, as projected in 2061, Singapore's water demand is likely to double, and projected demand for both industry and commercial would take up roughly 70% of the demand, with households taking up 30% of the demand. This could be a combination of the expansion of the industry and commercial sector in the future, while more effort needs to be put in place to encourage water conservation among households Nonetheless, PUB has consistently been able to achieve the target it has set to reduce the nation's water consumption per capita through public education and engagement programs for schools homes and commercial offices to encourage water conservation practices. In 2009, PUB also implemented the mandatory Water Efficiency Labelling Scheme, which requires manufacturers and retailers to inform consumers of the efficiency level of their products, such as washing machines, taps, urinal flush valves and so on. Unaccounted for water remains low at 5%, which is among the lowest globally. Dissipated energy is relatively high and correspondingly larger than unaccounted for

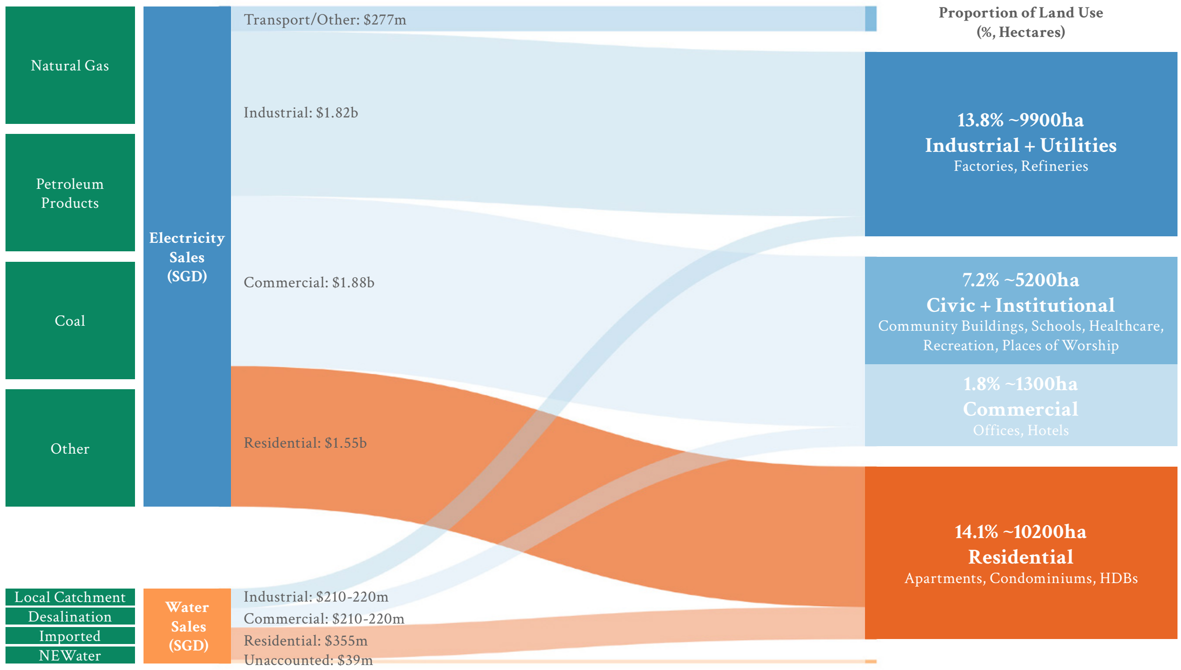


ACTUAL STEAM PLANT



IDEALIZED STEAM PLANT

55. SANKEY DIAGRAM OF AN EARLY STEAM ENGINE



56. SINGAPORE'S ELECTRICITY, WATER AND LAND USE BY SECTORS (2017)

water. These proportions also reflect the city state nature of Singapore as an object of analysis. After all, with the land area for residential, commercial and industrial development taking up only about 36.9%, it is important to note that Singapore is a land-scarce island without a natural hinterland. Therefore, the city-state also has to allocate land for other national uses such as for defence, national port and airport, nature reserves, parks and reservoirs. Many of these land uses are beyond the scope of this diagram yet are critical in ensuring a balanced ecosystem and sustainable environment, which therefore has a consequential impact on Singapore's water supply especially within the local water catchment.

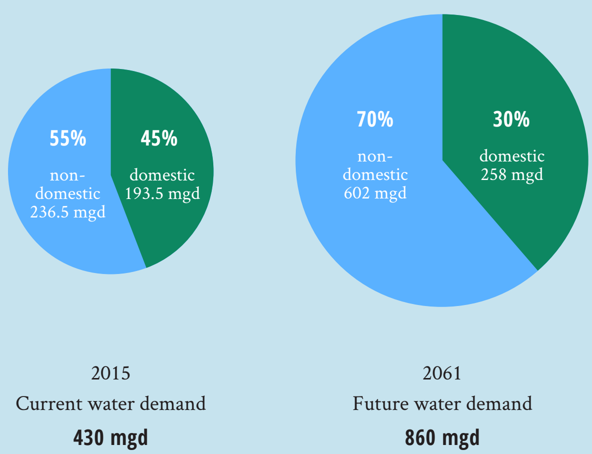
Outside of the internal representation of the national taps, total water demand including virtual water associated with the importing of food from crops and livestock, as well as from industrial production must also be incorporated into the consumption picture. One estimate places the total net virtual water import figure at 11,781 million cubic meters of water per year and across a period from 1987 to 2001. This compares to a demand within the island of around 430 million gallons per day, or roughly 766.8 million cubic meters per year, a relatively small proportion of the grand total including the virtual water volume. Of this the bulk is again in industry and industrial products with only 0.03 percent of the net virtual water importation equivalent being consumed on the island by livestock and crops, or the basic food component.[43] This might also seem to be something of a justification to move away from local food production in the 1980s described earlier, in favor of the industrial and service sectors and with much higher added value of production. Nevertheless, these figures also illustrate the extent to which Singapore's effort to reach water sustainability in the domestic sector is both localized and of strategic importance. It also illustrates one of the trade-offs in pursuing such a strategy within the broader international scheme of things.

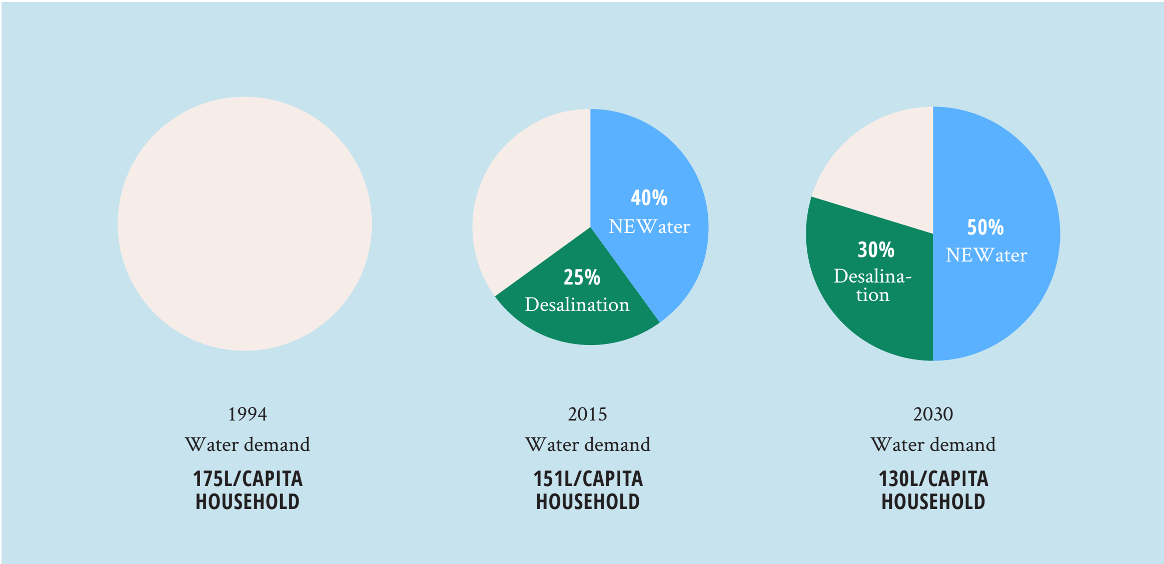
e.

SUSTAINABILITY, DEPENDENCIES AND VULNERABILITIES

Despite the time-bounded agreements for water supply from Malaysia, Singapore continues to strive to achieve water sustainability by 2061. This is the case under the scenario of a doubling of expected water demand from the present to 2061, or from 430 million gallons per day to 860 million gallons. Indeed, further downward movement on the sensitivity of factors driving demand such as water conservation per capita by five to seven percent, and island population by 20 percent and predominantly among non-residents, could lessen the overall demand to 640 million gallons per day and within projected downward shifts in the proportion of domestic water use to 30 percent by 2061, domestic demand by households would remain at current levels of around 194 million gallons per day.[44] Any water supply scenario moving forward will incorporate a different proportion in the mix of tap supplies than today. In fact, judging from some projections the degree of reuse will shift upward appreciably from 44 percent or so at present to around 72 percent in 2061. However, this seems able to be accomplished under the reference designs for NEWater and desalination plant operations in the future, including likely technical improvements. The inclusion of virtual water requirements, nevertheless, alters the rosy picture appreciably with an estimated 11,781 million cubic meters per year of virtual water added to the current 767 million cubic meters per year of island water demand.

Major among the dependencies of water with other sources and stocks of supply are energy





57. SINGAPORE'S WATER DEMAND AND SUPPLY STRATEGY, 2015 AND 2030

use, population and food, as well as industrial products in the case of virtual water demand. Energy demand, though seemingly a real issue during the early days of non-conventional water treatment, has abated to levels slightly above current practice, but not alarmingly so, with newer technologies. The replacement of highly energy-consumptive reverse osmosis processes with newer electrodialysis-electroionisation techniques puts treated reused water in the range of 1.8 kwh per cubic meter of water and 0.75 to 0.95 kwh per cubic meter overall.[45] Without any abundance of local energy supplies the major trade-off is land base necessary for storage, refining and production facilities, as well as any residuals of disposal of this production in the form of air and water pollution. On a small island it might be argued that such facility presents one an issue of needless competition with higher-value uses. However, so far, this does not appear to be the case. In fact, piece-meal technical advancements, such as the Deep Tunnel Sewage System work in the opposite direction both with regard to energy use and land conservation.

Population growth in Singapore has been advancing at around 2.0 to 2.5 percent per annum, standing now at 5.7 million or so inhabitants. Continuation of the overall and espoused growth policy will require around 15,000 to 25,000 new citizens each year, particularly as the hoped for 2.1 Total Fertility Rate (TFR) has never been reached with TFR today standing at only 1.2. Furthermore, the aging population, especially of 'baby boomers' is at a cross-roads, with a further 900,000 people expected to exceed 65 years of age before 2030.[46] One upshot will be the continued need for in-migration in order to maintain levels of social welfare, if not material well-being. Another outcome, however, might also be some containment of this in-migration particularly of non-residents in Singapore because of other strains placed on the welfare of the city-state by way of physical development, housing, congestion and basic supplies of resources like energy, water and land. Currently Singapore, with around 8,041 persons per square kilometer, is the second sovereign state in density, just behind Monaco. The likely proportion of non-resident population is estimated by 2030 to be on the order of 45 percent, and has been on the rise as shown in the accompanying table. This is also alarming to some. Indeed, some slowing down in population may serve Singapore well among other forms of growth and generally fit a broad model of striving for quantity at first, followed by higher consideration not just of numbers, but the quality of added contributions. As indicated earlier, reduction in the role of population growth alone accrues benefits to the water supply and demand perspective.

To be sure in this 'green-blue' story of Singapore and in its development more generally, tradeoffs have been made, either consciously or not, among the economic, social and environmental interdependencies that constitute and, in fact, describe and define the island state. As noted earlier, Singapore is not renowned for any particular brand of goods although it is a popular destination for business, consumption and tourism. It has a highly qualified work force and society, but its economic intensity is moderate to high, although not very high in comparison to other world cities. New York, for instance, though far more numerous in population is also considerably more intense. For Singapore to improve and to offset potential negative trends involved in moving away from growth policies, will require higher efficiencies, innovation, and potential automation. It may also require rescaling of aspects of essential services, much like the Deep Tunnel Sewage System has for treated and reused water. Simply in terms of competing uses on a small land base, limits to technical supplies and deliveries, and the like, there are limits to continued growth. Moreover, as a persistent and widening destination for a particular band of services, modes of consumption and leisure, there seems to be the very real potential of falling into what might be described as a 'high-to-mid-level trap', where further significant advancement is limited. Such an outcome, however, may not be such a bad thing, but it is one in which the very strong and profound influence of water sustainability and the environment on the national narrative have come into play.

NET VIRTUAL WATER IMPORT (1997–2001)	TOTAL (104 M3/YEAR)	PER CAPITA (L/P/DAY)
CROP PRODUCTS	2,386	1,634
LIVESTOCK PRODUCTS	1,461	1,000
MEDICAL PRODUCTS	7,934	5,435
TOTAL	11,781	8,069

58. SINGAPORE'S VIRTUAL WATER USE

A related potential vulnerability is in the domain of virtual water consumption and what it implies by way of other dependencies, although responsible consumption is probably more apt here as a basic concept. With regard to food, crops such as wheat and rice, can be distinguished from livestock, including chickens, pork and eggs in Singapore's case. As it turns out Singapore imports a substantial amount of wheat from Australia which uses two times more water on average than another source like the United States. Most rice in Singapore is also purchased from Thailand where the virtual water content is also high, although it is less productive per unit of crop production than non-exporting China and India.[47] Total virtual water consumption for livestock is significantly lower than for crops, at 1,461 million cubic meters of water per year compared to 2,386 million cubic meters. Also diet plays a role here with substantial amounts of chicken and pork being imported, although with a consumption of eggs that is about one tenth that of Europe. With regard to industrial products, by far the largest consumer of virtual water content at 7,934 million cubic meters of water per year, on average, different trading partners have different levels of virtual water content with the United States, for instance, at 100 liters per US$, compared to Germany and the Netherlands at 50 liters per US$ and a broad range for other countries from 10 to 151 liters per US$. Construction materials, mostly imported into Singapore, are relatively high in virtual water content and cotton, used in clothing, is extraordinarily high. In general there are two approaches that can be taken towards responsible consumption of virtual water. The first would be striving to achieve high levels of food self-sufficiency. As narrated earlier, this was broken off in the 1980s in order to pursue a 'clean and green' Singapore as much as anything. Prior to that the nation was self-sufficient in chicken, pork and eggs, as noted. Given the failure of attempts to pursue high-tech agriculture in Singapore, the likelihood of successful further pursuit of self-sufficiency seems to be low, although not impossible, given some less land-consumptive forms of vertical agriculture. A second broad strategy is to introduce virtual water content into consideration in trading agreements with various nations for foodstuffs and products. Some other existential threats to Singapore's blue-green picture may also be seen to come from climate change, sea level rise and other weather perturbations. However these will be dealt with in a later chapter.

endnotes

1. Oon, C. 2009. Key step to water adequacy. *Straits Times*, June 24
2. Lenouvel, Vincent; Michel Lafforgue; Catherine Chevauche and Pauline Rhétoré. 2014. "the energy cost of water independence: the case of Singapore" *Water Science and Technology: a journal of the International Association on Water Pollution Resources*. 70:5, p.789.
3. Lenouvel et al., p.789.
4. Interview with Mr. Harry Seah, Director of Technology of PUB on 6 February 2017.
5. Tan, Irene. 2016. *Beyond Singapore's blue-green matrix: an international comparison of blue-green systems in Melbourne and Singapore* (Unpublished paper, 14 July).
6. The Public Utilities Board was set up as a statutory board in 1963 to provide electricity, piped gas and water supply for Singapore. In 2001, the electricity and gas undertakings of the Public Utilities Board were transferred to a newly set up statutory board called the Energy Market Authority. The Public Utilities Board was then reconstituted as the national water agency, known officially as PUB, Singapore's National Water Agency. The idea was for PUB to manage Singapore's water supply, water catchment and used water in an integrated and more holistic manner.

   Based on an interview with Mr. Tan Gee Paw, Chairman, PUB on 9 February 2017 and Channel News Asia. "PUB to expand groundwater monitoring network" (26 May 2016, 11:23 am).
7. Lenouvel et al., p.789.
8. Lenouvel et al., p.787.
9. Allan, J. A. 1998 (2005) "Virtual Water: A Strategic Resource, Global Solutions to Regional Deficits". *Groundwater*. December, pp. 545-546.
10. Hoekstra, A. Y. and A. K. Chapagain. 2007. "Water Footprints of Nations: water use by people as a function of their consumption patterns". *Water Resources Management* 21:1, pp. 35-48.
11. Vanham, D. 2011. "How much water do we really use? A case study of the city-state of Singapore. *Water Science and Technology-Water Supply*. 11:2, p.234.
12. Lenouvel et al., 2013, p789.
13. Based on assumption of author in Lenouvel, p.789.
14. Lenouvel et al., p.789.
15. Microfiltration is a type of physical filtration process where a contaminated fluid is passed through a special pore-sized membrane to separate micro-organisms and suspended particles from process liquid.
16. PUB, "Innovation in Water Singapore", June 2011, https://www.pub.gov.sg/Documents/InnovationWater_vol1.pdf
17. Water: From Scarce Resource to National Asset, Urban Systems Studies Booklet Series. Singapore: Cengage Learning Asia, 2012.
18. Lenouvel et al., p.786f.
19. Lenouvel et al., 2013, p789.
20. Vanham, P.269.
21. Lenouvel et al., 2014.
22. PUB, 2016.
23. Vanham, p.289.
24. Seah, Harry; K. L. Khoo; J. Y. Chua;mD. Toh and S. C. Chua. 2010."Cost effective way to harvest estuarine water: variable salinity desalination concept" *Aqua – Journal of Water Supply: Research and Technology* 59:6-7, pp.453-454.
25. Seah, p.458.
26. Machuca, Lubomir and Vit Fara. 2014, "Combination of Electrodialysis and Electrodeionization for Treatment of Condensate from Ammonium Nitrate Production." *World Academy of Science, Engineering and Technology International Journal of Energy and Power Engineering*, vol 8, no 6, pp. 485-487.
27. Siemens. 2017. *Ingenuity for Life: Our History in Singapore*. https://www.siemens.com/ and "Siemens to develop innovative sea water desalination technology" (Monday, June 23, 2008).
28. Based on an interview with Ms. Olivia Lum, Founder of Hyflux on 15 August 2017.
29. Public Utilities Board. 2016. *Our Water, Our Future*. (Singapore: Public Utilities Board).

30. Interview with Ms. Linda De Mello, Deputy Director, 3P Networks, PUB on 16 August 2017.

31. Interview with Mr. Harry Seah, 6 Feb 2017.

32. Seah, p.452-458.

33. Lenouvel et al., p.792.

34. Based on an interview with Mr. Yong Wei Hin, Director of the Deep Tunnel Sewerage System Department, PUB, on 22 June 2017.

35. Interview with Mr. Hin.

36. See data in accompanying tables.

37. Lemonick, S. Drinking toilet water: The science (and psychology) of wastewater recycling. *Earth Magazine*, [online]. Available at https://www.earthmagazine.org/article/drinking-toilet-water-science-and-psychology-wastewater-recycling.

38. Remainder of the paragraph based on Vanham, p, 222.

39. Vanham, 2011 (p22).

40. "Sankey Diagrams",https://en.wikipedia.org/wiki/Sankey_Diagram. Also see, Schmidt, Mario. 2008. "The Sankey Diagram in Energy and Material Flow Management, Part 1: History" *Journal of Industrial Ecology* 12:1, pp. 82-94.

41. Corbett, John. 2001. *Charles Joseph Minard: Mapping Napoleon's March, 1861*.(Washington, DC: Centre for Spatially Integrated Social Science).

42. 43% of water is estimated to be sold to households; 5% of water is unaccounted for; and the remainder is split among industrial and commercial users. We used domestic and non-domestic water prices for these two categories. Based on PUB's recommendation, we treat water sold for resupplying ships, though non-zero, as negligible. Annual sales total around $785 million. We assume that unaccounted-for water (which may include leaks, flushing or other losses) is equally spread throughout the system, so if that water were to be sold, it might be worth around $39 million. The 5% of water unaccounted for in the system reflects an extremely low rate of lass by global standards. For electricity, in reality, there are both contestable and non-contestable electricity rates, with different shares of each sector subscribed to different regimes. Here, we have used the assumption that no residential households subscribe to conetstable electricity rates, but the majority of industrial and commercial use contestable pricing. Estimates for contestable expenditures relies on a simplified price based on Uniform Singapore Energy Price (USEP). Our electricity data is based on the twelve months of 2017. By the end of 2018, all of Singapore will be an open electricity market, which will also yield new pricing outcomes in the future.

43. Based on Vanham (2011), Allan (1998), Hoekstra and Chapagain (2007) and PUB (2016).

44. PUB. 2016. *Our Water, Our Future.* (Singapore: PUB).

45. H2PC Asia, n.d. Energy efficient seawater desalination in Singapore. Available at http://www.e2singapore.gov.sg/DATA/0/docs/NewsFiles/Energy%20efficient%20desalination.pdf

46. See Department of Statistics Singapore, *Population Trends*, 2017.

47. Paragraph based partially on Vanham, p.227 and p.45f.