DEEP TUNNELS AND ASSET MANAGEMENT IN URBAN SANITATION & STORMWATER MANAGEMENT:
Lessons from Paris, Singapore and London

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A number of big and dense cities in the world use ‘deep tunnels’ for collection, transport or storage of water in urban sanitation and stormwater management. In Paris, deep tunnels have existed since ±1900. In Singapore, the Deep Tunnel Sewerage System exists since 2008 and will be fully completed in 2025. In London, the construction for the deep Thames Tideway Tunnel started in 2016 and will be completed early 2024. Three different stories, three complementary approaches.
Amsterdam foresees increasing investments due to ageing sewerage in the dense old city. Learning from the experience of Paris, Singapore and London, can a deep tunnel attribute to simplify such a complex job or be a cost efficient solution? This was the key question of the Case Session at the Amsterdam International Water Week.

The three cities, Paris (Greater Paris Sanitation Authority SIAAP), Singapore (Singapore’s Public Utility Board PUB) and London (Thames Water and the new independent company, Tideway), have their own different experiences and approaches in the choice of using tunnels in urban sanitation and stormwater management. Why did they decide to construct deep tunnels? What is the relation between the specific tunnel solution and the circumstances like the density of the city, the future developments (climate change, growth of population), the soil condition, and the purposes concerning costs, efficiency, operation, real time control, maintenance, etc.?

To answer the question, we need to understand what is meant by ‘a deep tunnel’. In this consideration, the definition is used that ‘a tunnel’ is an underground passage or corridor of a length exceeding one hundred meters in which people can stand up and walk (> 2,00m), and ‘deep’ in these three cities, is about 30 till 60 m or even 100 m deep.

The deep tunnels have different purposes:

- as main infrastructure for waste water transport;
- as urban stormwater management for flood protection;
- as combined sewers to protect surface water receiving from pollution caused by Combined Sewer Overflow (CSO).

The city of Amsterdam doesn’t have deep tunnels for any of these purposes. Can a deep tunnel be an effective solution for the challenges of the city of Amsterdam? What can be learned from Paris SIAAP, Singapore PUB and the Thames Tideway Tunnel? In other words: why should cities think about planning and constructing deep tunnels?

This article aims to touch some important goals in the consideration of planning a deep tunnel in relation to water quality and quantity. At the same time it will make fantastic underground constructions visible!
A complete picture of the decision-making process would be extremely complex. For example, it consists of politics and several interests for today and the future (like sustainability or economics), or the influence of the financial situation, the culture, the organisation structure and ownership of assets in different nations.

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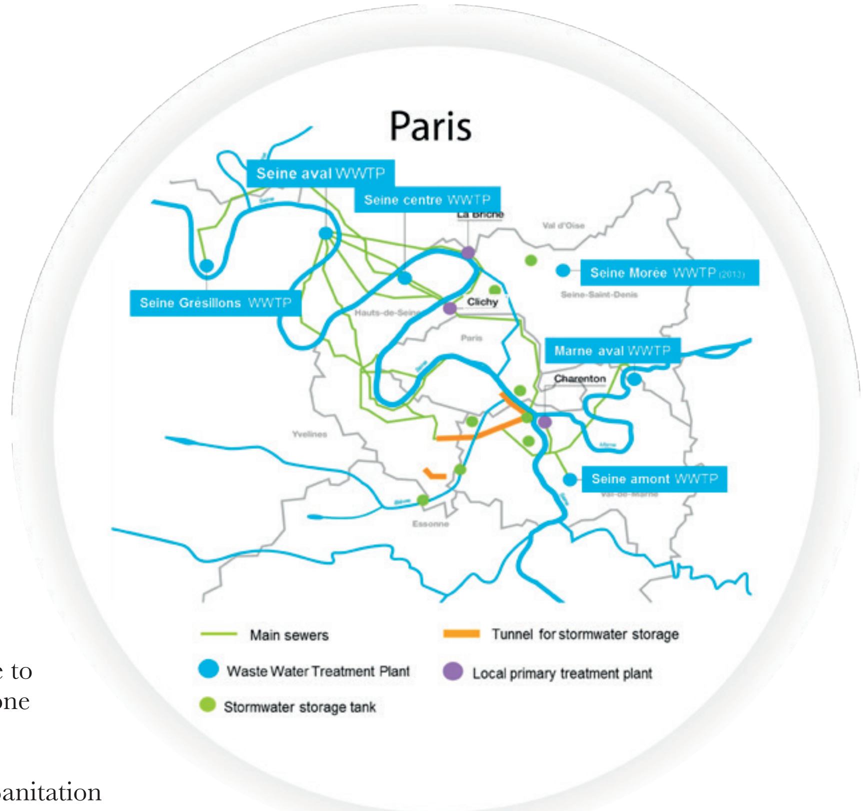


The story of Paris, deep tunnels as a legacy of foreseeing engineers

The Paris agglomeration has an important heritage of deep tunnels: several thousand kilometers of sewerage networks meet the definition, as explained before. From the 19th century the engineers at that time chose to make sewers accessible. The SIAAP is one of the heirs of this time.

Who is SIAAP? It is the Greater Paris Sanitation Authority. SIAAP is in charge of the final transport of wastewater of 9 million inhabitants to its 6 sewage treatment plants. SIAAP owns a sewage transport network of 400 kilometers long and the first galleries of its heritage were commissioned in 1893. Of this network 70% consists of combined sewers.

Several reasons explain the choice for deep tunnels. Originally, the search for good gravity flow conditions led the engineers to cut the meanders of the River Seine instead of following them. So, deep underground works became essential. The idea was that the amount of wastewater had to be transported to only one downstream waste water treatment plant. That led from the outset to large structures. Later, it is the congestion of the underground in the Paris region, which led to continue the development of deep tunnels in combination with the construction of 5 additional treatment plants. As a result, the length of tunnels continues to grow. Today, complementary tunnel projects are still under study.

The SIAAP tunnels are used primarily for the transport of wastewater. Some tunnels have also been built especially for the storage of stormwater, to manage pollution due to combined sewer overflow. Finally they will also serve in the fight against the floods from the sewer network.

In 2017 this structure with tunnels as important assets, made it possible to interconnect the sewage treatment plants. SIAAP has developed a large centralized management system for a real-time optimization of the operation of its sanitation system, called 'MAGES'. It is the essential complement for flow management between six treatment plants serving a collection area of 1800 square kilometers.

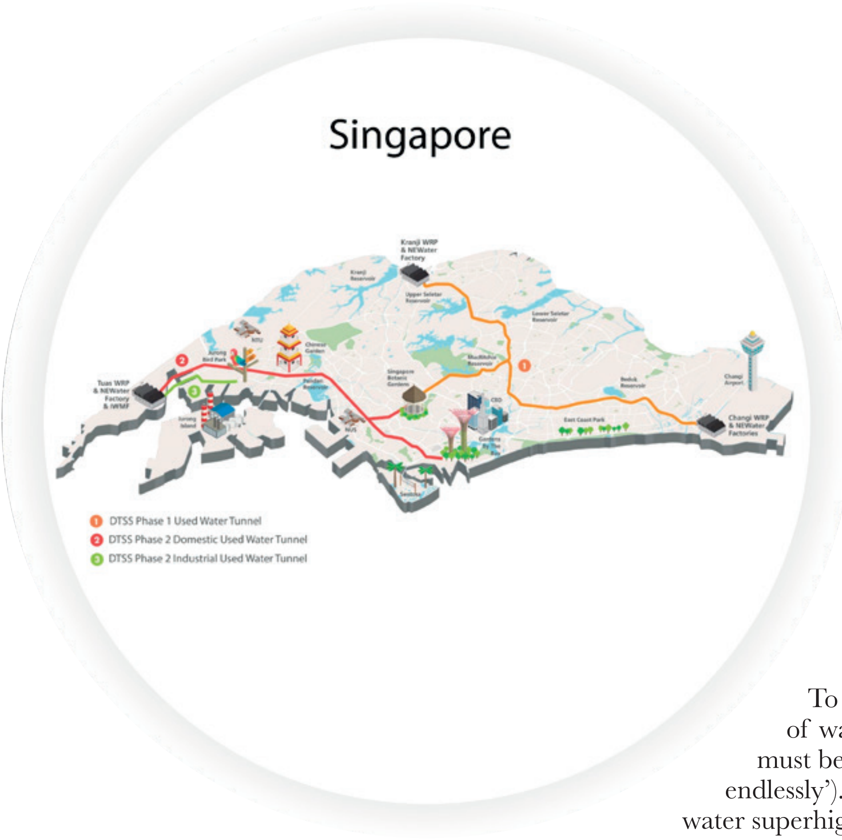
If these works are designed to last, the first ones are more than 100 years old, they are however subject to an inspection plan: each tunnel is visited once every 10 years. Among the sensitive points of the Paris network, two problems must be underlined:

- the production of gas: H2S and CH4 in trunks with too low velocity to avoid deposit of organic matter;
- the solid waste management in the tunnels, storing combined sewer overflows.

The topics under development are:

- the use of drones or remote-controlled machines to inspection works;
- the real-time control system to shift from a hydraulic management to a flow of pollutants management;
- the improvement of maintenance and its works to avoid odor emissions.

In the case of the Paris region, tunnels clearly appear as a reliable, sustainable and efficient solution for transporting urban wastewater, for managing stormwater pollution and for floods control in a dense city!



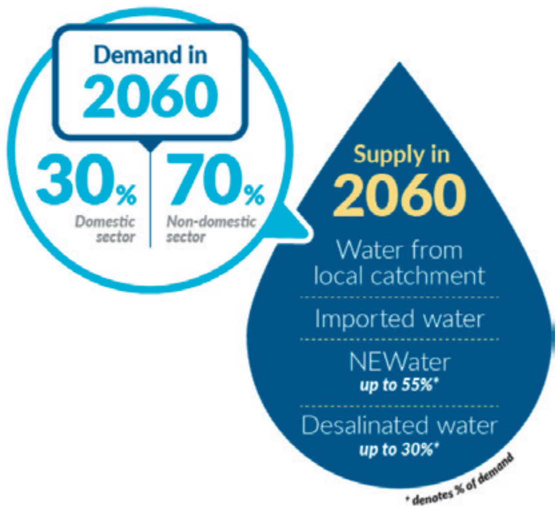
Water demand in Singapore is currently about 1,6 million m3/day with homes consuming 45% and the non-domestic sector taking up the rest. By 2060, Singapore's total water demand could almost double, with the non-domestic sector accounting for about 70%.

To assure a robust and diversified supply of water, also wastewater and used water must be used as a resource[1] ('reuse water endlessly'). For this reason PUB designed a used water superhighway for the future, the Deep Tunnel Sewerage System (DTSS). This is a cost-efficient and sustainable solution to meet Singapore's long-term needs for used water collection, treatment, reclamation and disposal. The design life is 100 years, or even more.

The story of Singapore, deep tunnels as a used water Superhighway for the Future

In Singapore's 50 years of independence, the water vulnerability has turned into a strategic asset. And still, challenges lie ahead, like dry weather and storms. Expanding and building is core business. In a forecast of the demand of water amounts, PUB designed as a solution DTSS, the Deep Tunnel Sewerage System. Who is PUB? PUB, Singapore's National Water Agency, manages the entire water loop through integrated planning and implementing water infrastructure ahead of demand.

The sewerage system in Singapore is 100% separated from the drainage system. Deep tunnel sewers convey the used water by gravity to centralized water reclamation plants (WRPs). DTSS comprises a network of link sewers leading to two major tunnels (Phase 1 & 2) criss-crossing Singapore with three large WRPs, located at the coastal areas at the northern (Kranji), eastern (Changi) and western (Tuas) ends of Singapore, as well as outfall pipes.



The treated used water is further purified into ultra-clean, high-grade reclaimed water, called NEWater, or discharged to the sea through outfalls.

DTSS Phase 1 (construction from 2000 – 2008) comprises a 48 km long deep sewer tunnel running from Kranji to Changi, the Changi WRP itself, two 5 km long deep sea outfall pipes and 60 km of link sewers. The treated used water is then discharged into the sea through deep sea outfall pipes or channeled to the Changi NEWater factory where it is further purified into NEWater.
DTSS Phase 2 extends the existing deep tunnel system to collect used water from the western part of Singapore including the downtown area and major upcoming developments such as Tengah Town and Jurong Lake District. When completed, it will have a conveyance system that is made up of 60 km of link sewers and 40 km of deep tunnels; as well as the Tuas WRP.

Upon completion of phase 2 (2014-2025), two existing conventional WRPs (Ulu Pandan and Jurong) as well as intermediate pumping stations, will be progressively phased out.
At the same time, Tuas WRP will be co-located with the National Environment Agency's Integrated Waste Management Facility (IWMF), to reap the potential synergies of the water-energy-waste nexus, maximizing energy and resource recovery. Like in Amsterdam, biogas and sludge are a fuel source to IWMF for incineration, the electricity generated is supplied to Tuas WRP for its operations.

In the case of Singapore, tunnels clearly appear as a reliable, sustainable and efficient solution for collecting and transporting urban wastewater in a dense city. They will free up land for expansion and they contribute to PUB's holistic approach to water management and so to the future needs for water in Singapore.

The story of London, deep tunnels as a long-term protection for the Thames

London has developed since the 1860s a combined sewerage system. Engineer Joseph Bazalgette's London sewers comprise almost 900km of tunnels (bricks) in the underbelly of London. The sewers diverted the city's sewage, via huge, elaborate pumping stations in north-east and south-east London, to treatment works and out into the estuary, well downstream of most of the population. In building this system, Bazalgette immeasurably improved public health and the atmosphere of London, banishing the 'great stinks' from raw sewage flushed into the river and averting the risk of cholera epidemics, which had plagued the city for centuries.

In the late 1860s, when the project began, London was at the tail-end of a population boom, with 2 million inhabitants, Bazalgette insisted on building enough sewers to cope with 4 million. Today, London has 8 million people, and the system now lacks the capacity to meet the demands of modern-day living.

Combined sewer overflows (CSOs) happen today more often than it did in Bazalgette's time as a result of increased population, changes in the way we use water and an increase in more concrete and sealed surfaces across the city. A system, that was designed to overflow only when the rainfall level exceeded 6mm/hr, now discharges into the Thames with as little as 2mm of rain. The water quality in the estuary is often below the

	Paris	Singapore	London
Organisation and responsibilities	SIAAP: Greater Paris Sanitation Authority, public reference for the Paris area sanitation.	PUB: Singapore's National Water Agency manages the entire water loop.	Tideway: organisation delivering the Thames Tideway Tunnel Thames Water: organisation providing water and wastewater services.
Mission / vision of the water companies	Together we create the future. We seek to fully deploy the potential of sanitation for the benefit of people, the city and the environment.	Integrated Management of Entire Water Loop through integrated planning and implementing water infrastructure ahead of demand.	To clean up the Thames and to promote a change in the relationship between London (and Londoners) and their river.
Goals for water quality and quantity	The transport of wastewater and the storage of storm water to manage pollution of the River Seine and the fight against the floods.	To meet Singapore's long-term needs for used water collection, treatment, reclamation and disposal: capture every drop of water, reuse water endlessly and desalinate seawater.	A long-term protection for the River Thames (among other things based on the EU Water Framework Directive).
Main challenge	To adapt existing Paris' sanitation to its future challenges with the legacy of foreseeing engineers.	To have a long-term used water system which comprises a network of link sewers leading to 2 major tunnels (a used water superhighway) and three large water reclamation plants.	To build a new sewer (deep tunnel) for London, to prevent the frequent pollution (CSO's) of the River Thames.
Deep tunnels	From 1893 and new projects are undergoing	DTSS: Phase 1: 2000-2008 Phase 2: 2014-2025	TTT: 2016 – 2024
Length **Size** **Depth**	136 km Ø 3 – 4 m and 59 km > Ø 4 m 30 m and can reach > 100 m	48 km and 40 km Ø 3 – 6 m 20 – 55 m and 35 – 55 m	25 km Ø 6,2 – 7,5m 35 – 75 m
Type of water in the deep tunnel	Mixed: wastewater + storm water	Wastewater	CSO mixed: wastewater + storm water
Design life	More than 100 years	100 years (or more)	120 – 150 years
Costs	---	Phase 1: S$3.4 Billion Phase 2: S$6.5 Billion	Sewage Treatment Works Upgrades – £700m Lee Tunnel – £600m Thames Tideway Tunnel – £4.2b
Treatment capacity	2,4 Mm³/d in dry to light rains conditions (high quality treatment) 3.8 Mm3/d, full biological treatment capacity in rainy condition (meeting UWWTD* directive standards) 5,3 Mm³/d in rainy condition Population treated 9 million	Changi: 900.000 m³/day Tuas: 800.000 m³/day Population treated 5,5 million	Peak capacity 40 m³/s Population treated 8 million

*UWWTD=Urban Waste Water Treatment Directive 1991

standard stipulated by EU directives. It leads to damage in the river's ecosystem and to public health concerns.

To counter this, following a series of studies the solution selected was a tunnel bored under the river, keeping the capital clean and healthy into the 22nd century. Thames Water is the company that provides water and wastewater services to London and the Thames valley with Tideway, a new independent company established to deliver the Thames Tideway Tunnel (TTT) project. The construction started in 2016 and will be completed early 2024. Thames Water will ultimately operate the system when it is connected to their existing sewerage network.

The Thames Tideway Tunnel is planned to run a 25km route (from Acton in the west to Abbey Mills in the east), mostly following the line of the river. It will run from 35 m underground to 75 m with a drop of 1m for every 790m. This is enough of a gradient to ensure the tunnel is self-cleaning – the current will sweep solids along with it, preventing fecal matter from festering and conditions becoming septic. It is also below the level of all the existing CSO tunnels.

These will be connected to the main tunnel by vertical shafts which will intercept overflows from the shallower sewers and carry them down into the deeper tunnel. Its diameter will vary from 6,2m to 7,5m along its length. The system has a design life of 120–150 years, a long-term solution.

The tunnel complements extensions to 5 wastewater treatment works that were delivered by Thames Water in the period 2010-2015, including 'Beckton' where the tunnel contents will be treated. Intercepting 34 CSOs, the Thames Tideway Tunnel goes through 14 London boroughs. It goes only under 1.301 buildings and will go through clay in the west, mixed sands and gravels in the central region and chalk in the east. It will handle 1,5 million m³, even though it should only fill to capacity about seven times per year; it also acts as storage for smaller storm events.

In the case of London, deep tunnels clearly appear as the best and most cost-effective way of dealing with the Combined Sewer Overflow problem in a reasonably short timescale and achieve the water quality in the Thames the EU demands.

The story in Amsterdam, what problems will deep tunnels solve.....

Waternet, watercycle company in Amsterdam, adopted the method of asset management in the field of wastewater, storm water, drinking water and surface water. The mission of Waternet is 'to gain together from water, together with our customers and partners we achieve more'. Waternet applies the method of asset management for all the assets that are needed to accomplish the tasks.

The basics for transparent long-term plans are risk management and a solid area assessment with a focus on the assets. The guideline is the so-called 'three level approach', an assessment on 3 levels: the complete system, the network and the object level. The assessment concerns 5 considerations: what will the future bring, are the assets ready for the future, which assets are or will be critical, what will be the strategy (minimum Life Cycle Cost) and what is the priority of investments?

So, Waternet considers the investments for assets as part of the integrated system, together with customers and partners. In this article we focus on the planning of deep tunnels in the relation to the goals for water quality and quantity. What problems can a deep tunnel solve in the city of Amsterdam? Regarding the challenges of the upcoming replacement task in this dense city, with its settlement and its flat ground level, should Waternet consider to construct a deep tunnel under Amsterdam, to collect wastewater and storm water and transport it by means of gravity to the wastewater treatment plant? From the point of view of asset management and the three level approach: is a tunnel the best long-term solution in the functioning of the system and the network within the integrated task from Waternet concerning water?

The challenge in Amsterdam is sewer replacement on a large scale in a dense city, expected in the next decades, in narrow streets with old houses (partly World Heritage Unesco) and a structure that has developed historically over 100 years. After the initial choice of a combined sewer system in ±1900, the city continued constructing a separated system from ±1925. Nowadays 30% of the system is combined and 70% separated. In the period 1995-2005 about 34 storage bassins have been built behind the CSO's to reduce the pollution of the surface water in the canals.

The ground level in the city of Amsterdam is very flat. It varies between 0m and 1m in the old city center up to 0m and -1m in the more recent surroundings. This implicates that collecting and transporting waste water by gravity cannot follow the ground level.
Settlement is the most important factor for the replacement of the sewers. The principal sewers are founded on piles. The connecting smaller sewers without foundation (reasons: too expensive, lack of space, streets with bumps) are subject to settlement. Monitoring is needed to verify the remaining slope and the connection between the founded sewers and the connecting sewers.

The flat ground level, the settlement, the density of the city, the risks and the construction costs resulted in a so called 'sawtooth structure'. The sewers are designed with gradient and maximum depth of ±5m. At that point a pumping station transports the waste water to a nearby sewer with higher elevation. The largest sewer is a pressure pipe Ø 1800 mm. The sewer system of Amsterdam has 575 pumping stations and 540 km of pressure pipes. This includes the principal pressure system, transporting the wastewater (partly combined with storm water) directly to the wastewater treatment plant.

Around the year 2000, Amsterdam decided to build a new treatment WWTP Amsterdam West near the

harbour area. The transport to this location was designed with the principal pressure system, that consists of 69 pumping stations and 200 km of pressure pipes (partly integrated with existing pressure pipes). It was realized in 2005/2006.
Two other plants were removed, nowadays houses are constructed at these locations. Furthermore, the conveyance of the effluent emission from these two WWTP's to the Noordzeekanaal (large surface water near the harbour area) had a very large positive impact on the water quality of the surface water in the canals. The WWTP Amsterdam West is located next to the AEB, Waste-to-Energy company. Biogas and sludge are a fuel source to AEB for incineration, the electricity generated is supplied to WWTP Amsterdam West for its operations.

Why should Waternet consider to construct a deep tunnel? What can be learned from Paris SIAAP, Singapore PUB and London Tideway?

Paris has to deal with the deep tunnels as a legacy. The system has grown and the functioning and utilization of the assets are optimized. To adapt it to the future challenges, monitoring and real-time control are very important. In the case of Amsterdam, the 'sawtooth structure', as a historically chosen system, grows and functions well. In 2005/2006 the system based on this concept has been reconsidered. The choice was to hold on to this structure and adapt it to the future, also together with the customers and partners.

Singapore needs to reuse every drop of water endlessly, as a need for the water supply. A long-term used water system which comprises a network of link sewers leading to a used water superhighway (the deep tunnel DTSS) and three large centralized WRP's is necessary to attribute optimally to this goal. Waternet has different and several resources for drinking water, with a large storage of water in the dunes. For now, this situation reduces for Amsterdam the priority of the use of wastewater as a resource for drinking water.

With the deep tunnel TTT, London reduces the pollution of the River Thames structurally, by collecting the CSO's from a 100% combined sewer system. In Amsterdam 30% of the system is a combined system and storage bassins have been built behind the CSO's to reduce the pollution of the surface water in the canals. And a very important fact is the previously mentioned conveyance of the effluent emission to the Noordzeekanaal.

Considering the key question of the Case Session: Can a deep tunnel be an effective solution for the challenges of the city of Amsterdam? In other words can it attribute to simplify the complex job in Amsterdam concerning ageing sewerage in the old city?
It became clear that the goals for water quality and quantity are very important in the choice for a long-term solution in Singapore and London. A deep tunnel is an indispensable part of the solution. However, long linking sewers or complex constructions are still needed to connect the new deep tunnel with the existing sewerage system.

Reveal the lay-out of your wastewater system and tell the story about it.

London, Singapore en Paris share their knowledge about deep tunnels. Imagine that we can make such fantastic underground assets visible for other cities worldwide!

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To conclude, at the moment Waternet reaches the goals for water quality and quantity with the existing concept and an associated long-term planning for replacement. Waternet will adapt it to the future, together with the customers and partners. A deep tunnel doesn't seem essential yet to achieve the goals in a more efficient way or facilitate the challenges. A deep tunnel can even complicate renewing or replacing ageing infrastructure in the old city of Amsterdam.

Still, Waternet must consider the effects of a tunnel solution on the existing assets, like the large amount of pumping stations, the 540 km of pressure pipes and for the future for the tunnel itself. Aspects to take in consideration should be removal, replacement and maintenance, in relation to the long-term design life and construction risks. The challenges in Amsterdam are a solid and robust long-term plan for replacement in relation to riskmanagement and structural monitoring of the principal pressure system.

1 The 'Four National Taps': water from local catchment, imported water, desalinated water, NEWater.

Paris