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Increasing Singapore's resilience to drought

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Recent Meteorological Droughts in Southeast Asia

Singapore, Southeast Asia's small, developed, densely populated, equatorial island nation, experienced a 2-month dry spell (meteorological drought) at the beginning of 2014. Although February falls within the relatively dry phase of the north-east monsoon season, the near-zero total of rainfall recorded at the reference meteorological station at Changi Airport was 160 mm below the long-term monthly mean (NEA, 2014a), resulting in the driest month since 1869. By mid-March, small streams in both forested and urban catchments ran dry. Open water bodies including ponds and reservoirs shrank substantially in size. The long-range prospects for 2014 were not promising, as an El Niño event was predicted to develop later in the year (e.g. Ludescher *et al*., 2014). Unprecedented in the minds of many, the dry spell should nonetheless be viewed as an uncommon reminder of Singapore's vulnerability to drought.

During the last major El Niño in 1997/98, dry conditions occurred along a broad belt extending from middle of the Indian Ocean, through insular Southeast Asia, past the Hawaiian Islands in the Pacific Ocean. The impact on Singapore was significant. Singapore rainfall in 1998 was 48% below the long-term average (NEA, 2014b). The highest daily temperature in Singapore's record, 36°C, was recorded in March of that year (NEA, 2014c). During that period, a large number of uncontrolled fires in Indonesia ignited in conjunction with the dry conditions throughout the region. An estimated 45 600 km^2 of vegetation was burned in the islands of Kalimantan and Sumatra (Heil and Goldammer, 2001). Haze, primarily derived from aerosols from these wildfires, blanketed Singapore, Malaysia, and southern Thailand, causing US$9 billion worth of losses in tourism, transportation and farming industry revenue (Wardani, 2013).

In June and July of 2013, wildfires in parts of Sumatra and Borneo—again partly arising from drier-than-normal conditions throughout Southeast Asia—produced another haze event in Singapore. The 3-h Pollution Standards Index (PSI) reached a record high of 401 on 21 June 2013, surpassing the previous record of 226 set during the 1997 haze event (BBC, 2013). During the 2014 dry spell, fires in Peninsular Malaysia also generated elevated PSI levels in Singapore due to prevailing NE winds. Fortunately, before the haze reached unhealthy conditions (PSA $>$ 100), the dry spell ended abruptly in mid-March with the advent of several rainy days.

Not only did heavy rains signal the end of the dry spell, they marked the beginning of wide-spread curiosity about the unpredictability of the weather, especially about the inherent linkage between haze and drought. Local media enquired about the cause of the dry period, the rapid swing from extreme dry to wet conditions, the causes of flash flooding, the likelihood of an El Niño, and the possible reoccurrence of haze (Ee, 2014). These wide-ranging questions reflected concern over both recurrent hazards (floods and haze) and Singapore's long-term capacity to sustain water consumption as the nation grows and prepares for climate change.

Differential Impacts of the Drought throughout the Region

Despite being a rare meteorological event for Singapore, little action was taken to preserve water during the dry spell, compared with neighbouring Malaysia and Thailand where extended dry spells and droughts are relatively common (Garbero and Muttarak, 2013; Zin *et al*., 2013). Water rationing was implemented in the Malaysian States of Johor, Selangor, Negeri Sembilan and the Federal Territories of Kuala Lumpur and Putrajaya (Goh, 2014). The agriculture sector was negatively affected, including palm oil, for which Malaysia is one of the world's key producers (Parija, 2014). Cloud seeding was attempted to generate rainfall in drought-stricken states (Goh, 2014). In Thailand, 20 provinces were declared drought disaster areas (National News Bureau of Thailand, 2014).

Meanwhile, in Singapore the response was markedly different. Water consumption advisories were sent only to commercial and industrial users (MEWR, 2014a). Water rationing exercises, last seen in the 1960s, were considered only as educational tools (MEWR, 2014b). In response, water consumption actually increased by 5%—likely (Saad, 2014) due to increased bathing for relief during warm weather and hazy conditions, together with increased watering in some managed parks and green spaces. The ability to maintain business-as-usual water consumption was testimony to Singapore's resilience to meteorological drought.

Water Resilience in a Changing Climate

Singapore is listed by the World Resources Institute as one of 36 countries in the world with high water stress (WRI, 2014), largely because of its dense population and the paucity of freshwater lakes and aquifers to extract fresh water. Despite recognition of high water stress, Singapore still uses more water per capita than many other countries (per capita domestic water consumption = $151\,\mathrm{l\,day^{-1}}$). Reducing demand has proven much harder than expanding supply in a country that has sufficient financial resources. Singapore invests heavily in water technology, international agreements, and responsible management (PUB, 2014). Their forward-thinking and innovative management plans provide adequate water for domestic, commercial, and industrial use, despite the baseline stress level (WRI, 2014).

At the dawn of Singapore's independence in 1965, the new state initiated one of the world's most remarkable water resource strategies to store as much water as possible, reduce use, and minimize unaccountable losses in the storage and reticulation system (Tortajada *et al*., 2013). This ongoing effort is now hallmarked by the Four National Taps System (Tortajada, 2006; Figure 1): (1) local catchment runoff water stored in 17 reservoirs; (2) water imported from the Malaysian State of Johor; (3) desalinization of ocean water; and (4) recycled grey water, called NEWater. This water management strategy undoubtedly bolstered Singapore's resilience to the 2014 dry spell, with the latter two taps making up

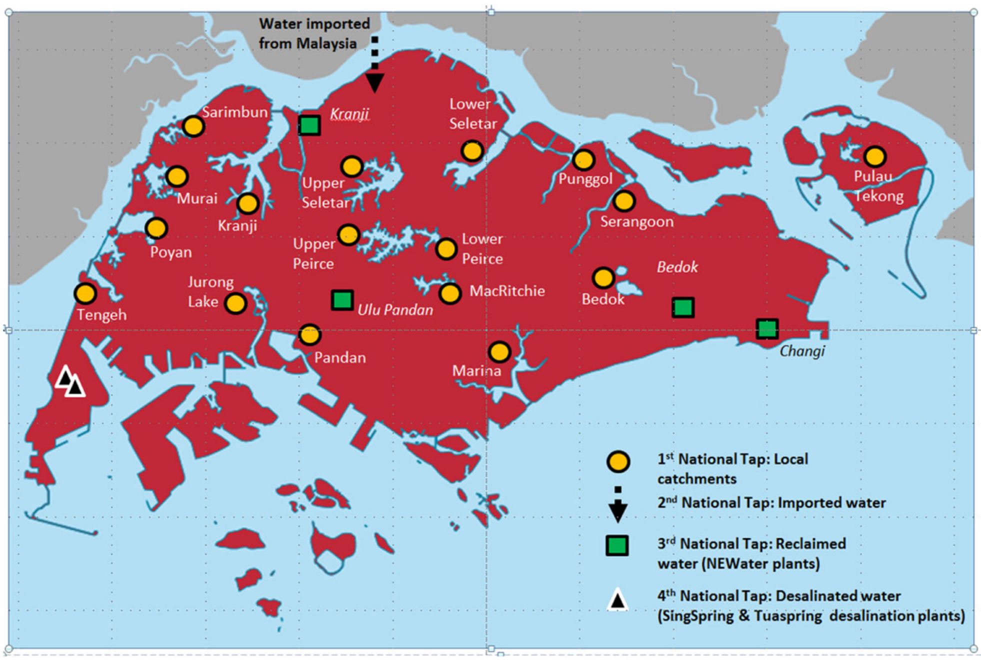

Figure 1. Locations of the Four National Taps of Singapore that supply the existing water demand

for shortfalls elsewhere in the system. Desalination output capacity was stepped up to >400 million litres a day (MEWR, 2014a,2014b), with the most recent desalinization plant coming online just a few months before the 2014 dry spell. NEWater production was also increased to the same level, some of which was available to maintain functioning levels in the reservoirs (MEWR, 2014a,2014b).

The Four Tap strategy should play an effective role in increasing resilience to water scarcity in the future if climate changes. Currently, the projected impacts of climate change for Singapore are uncertain, owing to the island's small size relative to the large regional domain of its governing climate (e.g. Trenbeth, 2010; Wilby and Dessai, 2010). Increased frequency of precipitation extremes, including heavy rainfall and dry periods, is commonly projected for the Southeast Asia region (e.g., Cruz *et al.*, 2007). Such changes in the behaviour of the hydrological cycle could greatly affect water resource availability and, correspondingly, increase vulnerability to drought. Although the occurrence of droughts in Singapore has been rare, the potential exists in the region.

Through paleoclimate analysis, Cook *et al.* (2010) illustrated that a $2.5° \times 2.5°$ grid encompassing the region of southern Peninsula Malaysia and Singapore has experienced severe droughts in 19 of the past 150 years (based on a Palmer Drought Severity index value ≤ -4). The probability of any year being part of such an event is therefore 13%. In addition, more frequent but less severe droughts appear to occur during the transition from La Niña to El Niño episodes (Sakai *et al.*, 2006). These findings demonstrate that despite a general assumption that dry spells are uncommon, Singapore is vulnerable to droughts of varying intensity.

Improving the Efficiency of the Four National Taps

The Four National Taps strategy worked well during the 2014 dry spell to reduce the impacts of dry conditions. However, these Four Taps will have to work harder in a changing climate, coupled with projected increase in water consumption and planned reduction of reliance on imported transnational water. Potential engineering strategies for water conservation include the reduction of evaporative losses from open water bodies. For example, the 17 reservoirs associated with Tap 2 have an open surface area of roughly 3000 ha. Evaporation losses from these water bodies are approximately equivalent to the annual rainfall of 1800–2200 mm. Thus, the potential loss of water from Singapore reservoirs is on the order of 54–66 million m^3 per year.

Some reduction of evaporative losses could come via multi-purpose floating solar systems on some open water bodies. Installation on the water surface cools the panels, and meanwhile shades the water, limits algal growth, and reduces evaporation. Proponents of this type of system laud the dual benefit of reduction in evaporative loss and solar energy generation. Research has already been conducted to determine the potential of applying organic monolayer films to reservoir surfaces to reduce evaporation. A pilot study at Bedok Reservoir, for example, concluded that such an approach could reduce water loss from evaporation by 30%, equivalent to 16–20 million m^3, at a cost of less than \$0.25 SGD per m^3 (Babu *et al.*, 2014). Elsewhere around the world, floating black balls have also been used to shade lake surfaces and reduce evaporation in areas where access and/or production of freshwater is expensive (Vara-Orta, 2008). Concerns with these types of engineering treatments are whether they are cost effective, impact aquatic ecosystems negatively, or are unsightly, thereby countering the goals of the Active, Beautiful, Clean (ABC) Waters Programme.

Initiated by the Public Utilities Board in 2006, the ABC programme aims to 'transform Singapore's reservoirs and waterways into beautiful and clean streams, rivers, and lakes' (PUB, 2009). Soft engineering solutions, including vegetated swales and bioretention systems that complement (or replace) traditional concrete-lined drainage systems, have been introduced under the umbrella of the ABC programme to reduce pollutant loads in runoff and promote infiltration of storm runoff water. The benefits of these practices may also strengthen drought resilience to an unknown extent. Cleansing is achieved through filtration as storm water percolates through unlined soil bottoms into the water table. When designed to enhance artificial recharge to below-ground stores, these systems convert water that is typically 'lost' into a groundwater store with a longer residence time (Bouwer, 2002).

An ongoing strategy to increase the effectiveness of the current Four National Tap strategy is to increase water use efficiency. The Public Utilities Board currently has initiatives to encourage people and industries to use water wisely. With a target to lower Singapore's daily per capita domestic water consumption from 151 to 140 l by 2030, water saving and conservation measures will clearly play an important role. To achieve drought resilience, however, awareness is also needed. Seeing drought as 'normal' in Singapore will be a challenge and may require a generation to achieve. Starting now is therefore imperative.

It may also be time for a national drought policy that puts greater emphasis on preparedness and risk management. Singapore's policies are similar to those in urban Australia, where rainfall variability is the highest of all the inhabited lands, except that the public in Singapore is not regularly exposed to the spectre of drought. That is, news bulletins do not report an index of climate that is correlated with drought, and there is no drought early warning system. Television weather reports in Australia include information about the Southern Oscillation Index, thereby sensitizing the public to the notion of rainfall variability, even where there is a large amount of water stored per capita. With respect to fine tuning a long-term drought resilience plan, Singapore may have missed an opportunity to promote sustainable water management during the 2014 dry spell. Implementing conservation measures then would have provided an element of drought awareness education to the community.

The Potential Role of Groundwater?

It will be a challenge to ensure that the Four National Tap system remains effective with additional climate stressors, particularly when coupled with other emerging socio-economic and political factors. For example, Singapore's population is expected to increase to between 6.5 and 6.9 million by 2030 (National Population and Talent Division, 2013), elevating the total demand for water disproportionally. In addition, the water compact that governs the purchase of fresh water from Malaysia ends in 2061, marking either the closure of the 2nd Tap or the renegotiation of a another water contract. It is projected that by 2060, 80% of Singapore's water will come from desalination and NEWwater (PUB, 2013). As these technocentric solutions are associated with very large capital and running costs, the recent dry spell possibly provides some incentive to consider looking for additional ways of harvesting water when needed.

The development of groundwater is proposed to strengthen drought resilience and national water self-sufficiency. The total groundwater reserves below Singapore and the immediate continental shelf are currently unknown. Projects are currently under way to investigate the groundwater potential of onshore Singapore areas, including the Jurong Formation in the southwest and the landfill of Jurong Island (Friess and Oliver, 2014). Post *et al.* (2013) concluded that offshore fresh groundwater reserves could be a global phenomenon. In the eastern half of Singapore, the Old Alluvium deposits form a potential aquifer system with fossil groundwater confined by the Kallang Formation (Figure 2). This fossil groundwater was formed in glacial times when sea level was lower and the entire Strait was exposed. Assuming an offshore area of 140 km^2, a net aquifer thickness of 20 m, and a porosity of 25%, the potential offshore groundwater reservoir is an estimated ~700 billion litres, which slightly exceeds Singapore's total annual water consumption of ~650 billion litres.

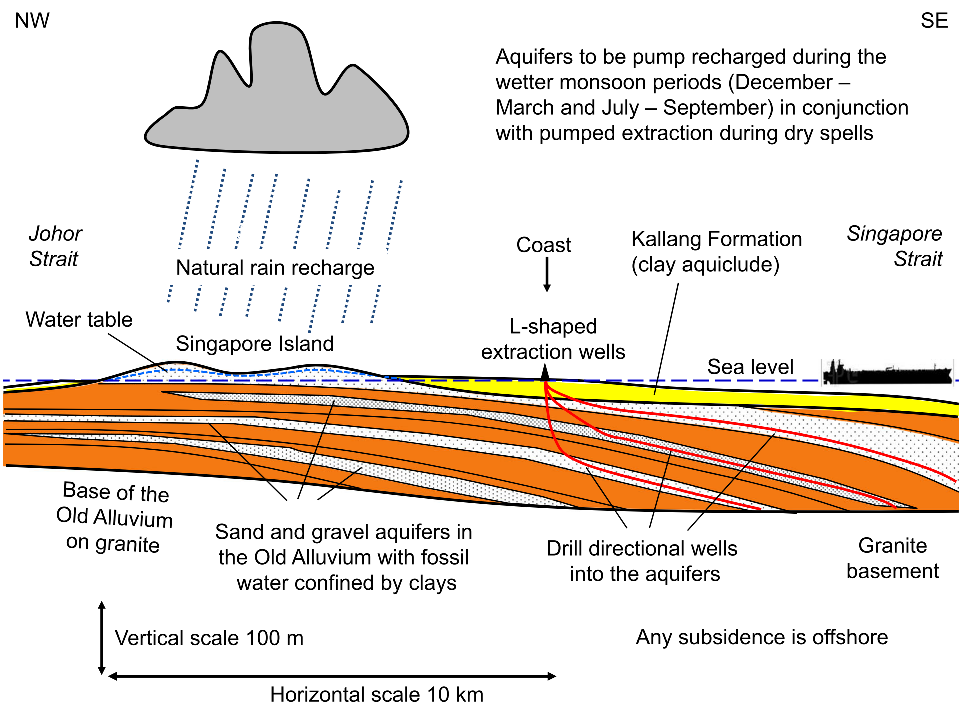

Figure 2. Concept for sustainable ground water extraction in Singapore from offshore confined aquifers of fossil water contained in the Old Alluvium formation beneath the Singapore Straits. Adapted from Friess and Oliver (2014).

Offshore groundwater could potentially provide a strategic water reserve in the event of unexpected dry spells. One conceptualization of a minimum impact approach to harvesting groundwater involves pumping in offshore locations below the Singapore Straits, where ground subsidence would be of limited consequence (Figure 2; Friess and Oliver, 2014). Other Asian cities including Bangkok, Jakarta, and Kolkata have experienced substantial subsidence because of over pumping of groundwater relative to recharge rates (Bhattacharya, 2013). For Singapore, pumped recharge could be carried out during the wet monsoon periods (December to early March and July to September) using excess surface runoff water that is normally discharged to the ocean. Recharging would balance the volume extracted during drier periods, ensuring longevity of this normally slow-recharging water source.

The 2014 dry spell as a reminder of future vulnerabilities

Looking back, the dry spell in early 2014 was timely in that it occurred at a moment when Singapore was pushing to increase its status as a regional leader in water production, development, and technology. The unanticipated dry period revealed a vulnerability that could hinder these aspirations. The meteorological drought was also a reminder of the potential for cascading hazards in a nation with only a handful of environmental threats. As prolonged dry conditions can lead to an increase in fires in neighbouring countries, they are inherently related to episodic haze events that represent serious economic and health risks.

Development of groundwater and the reduction in evaporative losses in open water bodies represent two internal avenues to address vulnerability to water stress, including droughts. Yet, reduction in lingering vulnerability to linked hazards such as haze will require external solutions. To date, there has been little progress in regulating burning in regional hotspots in Indonesia and Peninsular Malaysia. Singapore's leadership in water technology might, however, provide an incentive. Assisting neighbours to become more resilient to drought in the future may foster cooperation in reducing uncontrolled burning that occurs in their jurisdictions. This type of cooperation would be mutually beneficial to all countries in the region.

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